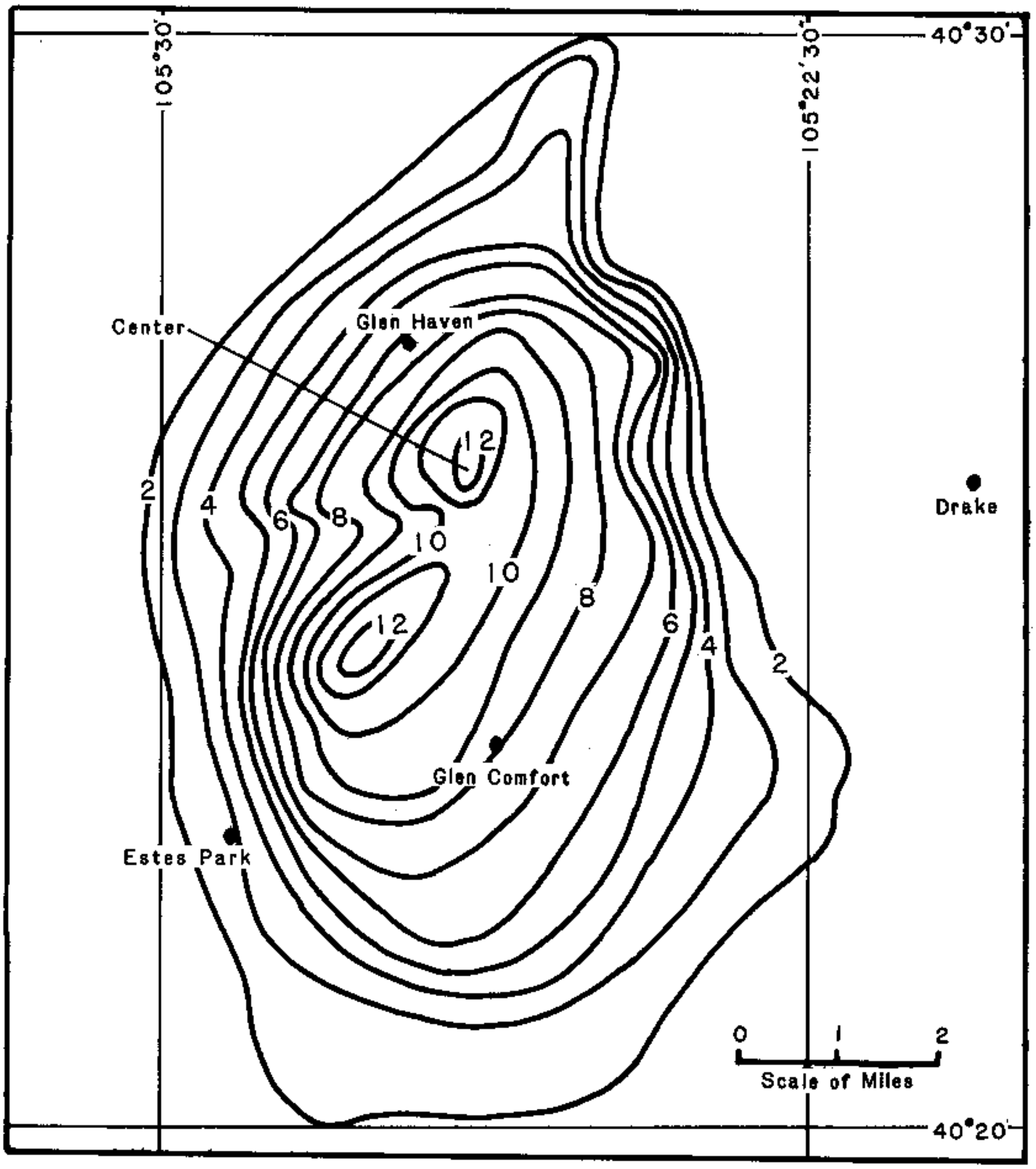


Figure 2.24.—Isohyetal map of intense 4-hr precipitation for July 31, 1976 - the Big Thompson, CO storm (81).

Mexico. By the morning of August 29, the surface winds along the Texas coast reflected the proximity of the approaching storm.

On August 29, a large maritime tropical air mass covered the eastern United States, while a polar mass of high pressure dominated eastern Canada. A weak Low was centered over the Great Basin and a polar air mass covered the Pacific northwest. During the afternoon of the 29th, thunderstorm activity began over eastern New Mexico as tropical air from the Gulf of Mexico was forced over the terrain. A few stations reported over an inch of rain by the end of the day. Thunderstorm activity decreased on the 30th, as the surface wind shifted to northeasterly under the influence of the tropical cyclone.

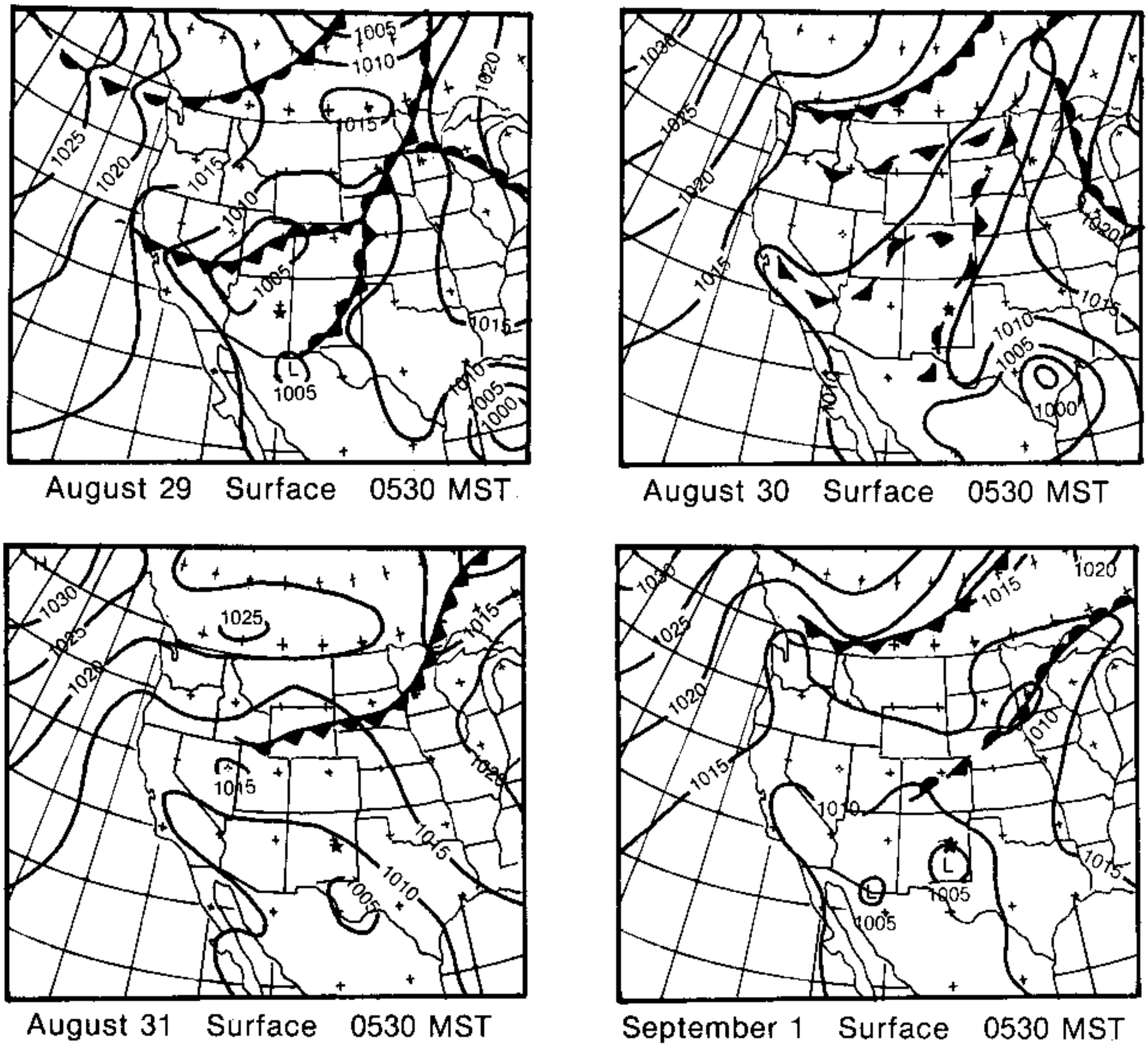


Figure 2.25.—Synoptic surface weather maps for August 29–September 1, 1942 – the Rancho Grande, NM storm (60).

The hurricane continued on the straight northwestward course and reached the Texas coast near Matagorda Bay slightly before 5:30 a.m. the morning of the 30th (fig. 2.25). Its movement remained northwestward at a speed of approximately 15 mph and its intensity decreased from hurricane strength to that of a tropical storm. The rain area accompanying the storm reached southeastern New Mexico late on the 30th and advanced steadily northward enveloping most of the lower Pecos Valley by the early morning on the 31st. The storm center itself entered New Mexico on the morning of the 31st and remained nearly stationary south of Roswell during the remainder of the day, with steady moderate rain north of the center. Late in the day, the storm began to move north-northeastward, steadily losing intensity. When it reached Tucumcari early on the following morning – September 1 – a cyclonic circulation was still evident. By this time rainfall had spread northward into southeastern Colorado and ended in the region south of an Albuquerque, NM – Amarillo, TX line. The final burst of rain in the storm consisted of scattered thunderstorms preceding and accompanying a cold front which approached from the north. The front moved across Colorado on September 1, and continued southward across Texas and New Mexico.

This storm was remarkable in that after traveling more than 700 mi over land, it still maintained a well defined strong cyclonic circulation, although no longer of hurricane intensity. Not a single station in the path of the storm reported thunder at the time of the heavy rain, indicating that large-scale convergence rather than local convection was the principal cause of precipitation.

The maximum precipitation for the 84-hr storm was 8.0 in. at three sites: Rancho Grande, Maxwell, and Chico, NM (fig. 2.26). The 2-in. isohyet encompassed over 35,000 mi^2, most of which was in the state of New Mexico. The maximum average depth of rainfall over a 1,000-mi^2 area for 24 hr was 6.8 in. The isohyetal analysis for this storm showed an orientation of the rainfall pattern from south-southwest to north-northeast, approximately paralleling the track of the storm and the mountain ranges.

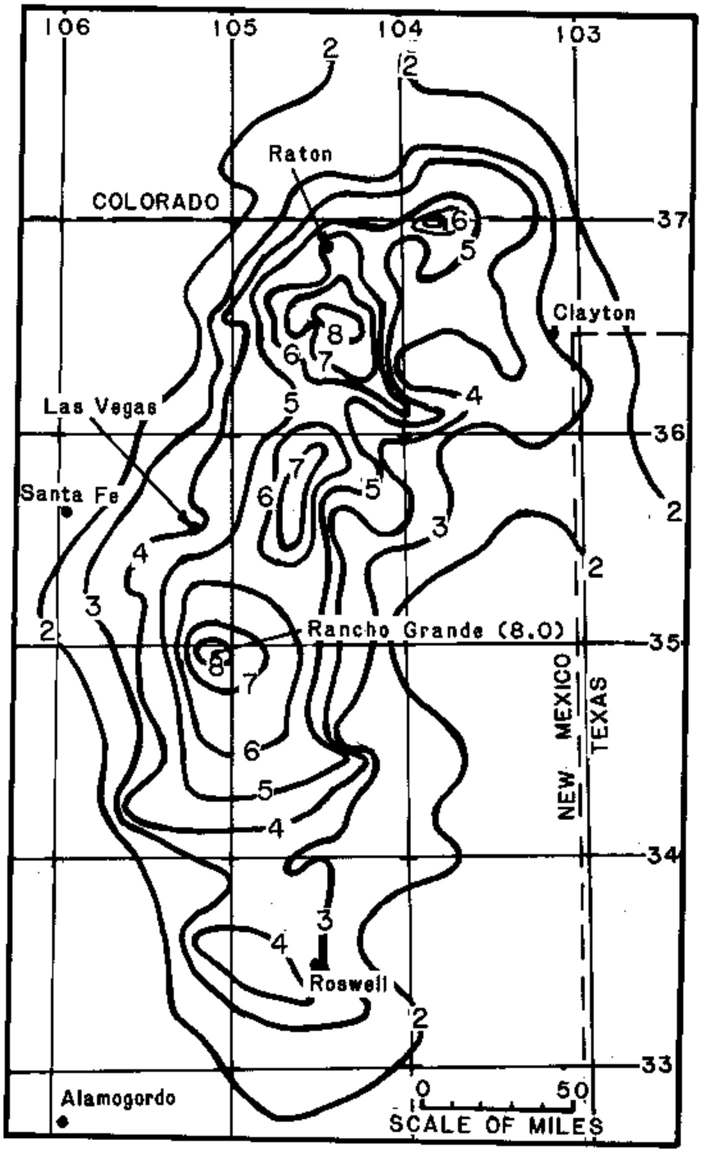


Figure 2.26.—Isohyetal map for August 29–September 1, 1942 – the Rancho Grande, NM storm (60).

2.4.2.2 Vic Pierce, Texas – June 23–28, 1954 (112). The depth of precipitation reported at Vic Pierce, TX for 10 mi^2 and 24 hr was 26.7 in. Precipitation from this storm was a direct result of the movement of Hurricane Alice from the Gulf of Mexico up the Rio Grande Valley. Heaviest rains occurred about 90 mi northwest of Del Rio, TX, during the period when the storm was losing its warm-core tropical storm structure.

On June 24, 1954 (fig. 2.27), a small hurricane in the western Gulf of Mexico 300 mi southeast of Brownsville was discovered by ship personnel. This hurricane, named Alice, moved from its birthplace on a track toward the northwest typical for this season and region. The storm crossed the coast some 50 mi south of the mouth of the Rio Grande, at about noon on the 25th (fig. 2.27), and proceeded up the short distance south of Brownsville, Larado and Del Rio, TX. The surface wind at Brownsville rose to nearly 50 mph while a pilot balloon measurement of wind speeds aloft showed a speed of 130 mph from the southeast at 3,500 ft. As the center passed Del Rio at noon on the 26th, the highest surface wind was 33 mph (the fastest single mile of wind). The low-level

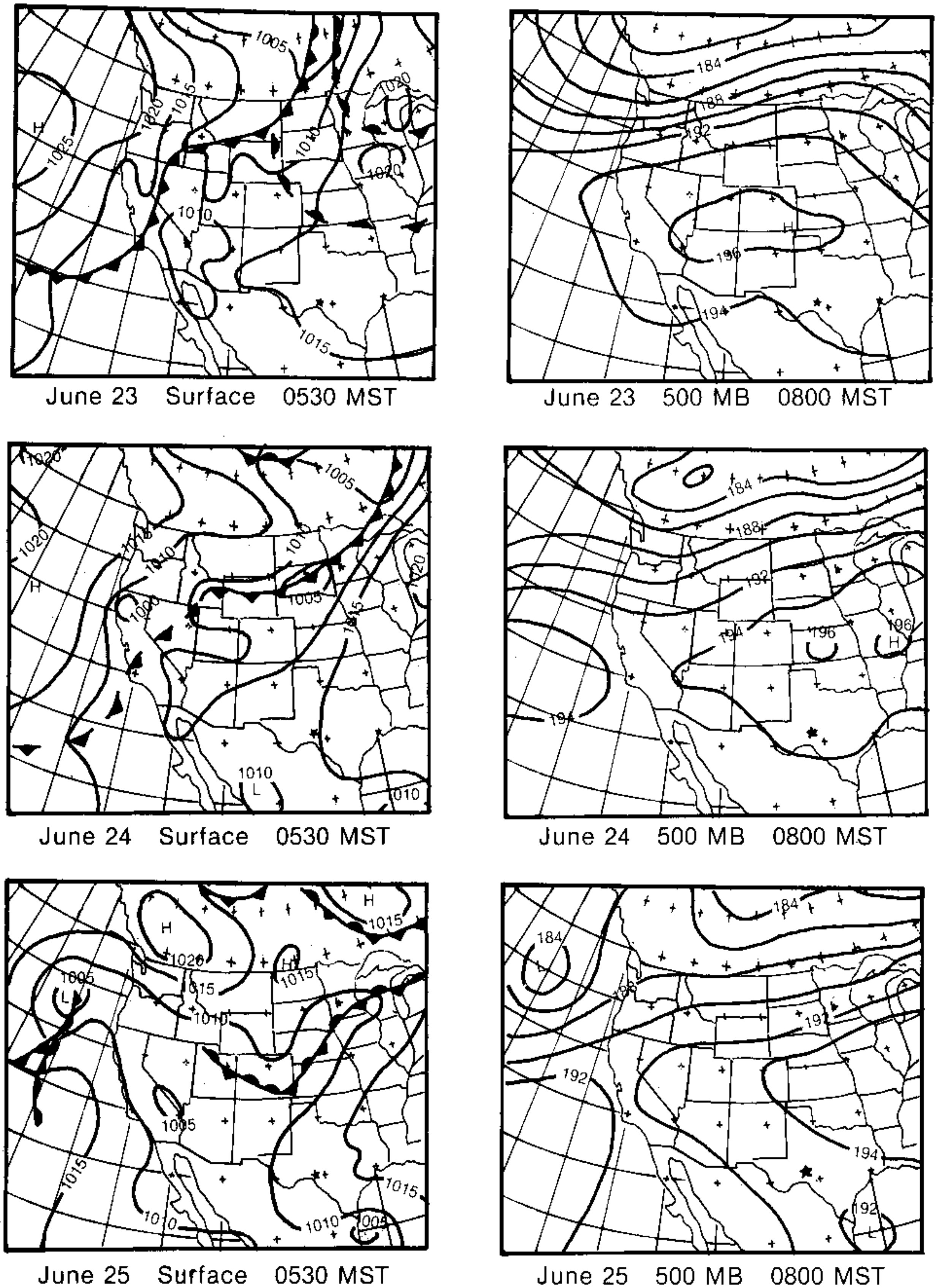


Figure 2.27.--Synoptic surface weather maps and 500-mb charts for June 23-25, 1954 - the Vic Pierce, TX storm (112).

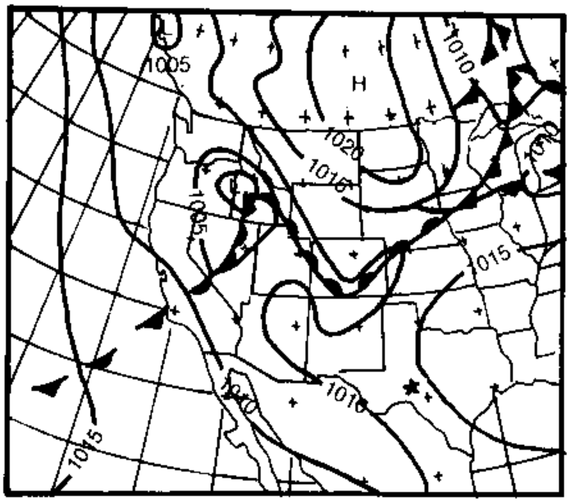
jet winds also diminished. The highest speed revealed by the 8:00 a.m. pilot balloon observation was 48 mph at 3,000 ft above sea level. However, the storm on this day still maintained its warm core as evidenced by the 500-mb temperature at Del Rio.

Continuing on its northwestward track, the storm crossed the Rio Grande to the region between the Big Bend of the Rio Grande and lower Pecos River. It stalled there during the night of the 26th and remained nearly stationary through the 27th. Early on the 28th (fig. 2.28), the storm remnants were barely discernible as a cyclonic wind circulation with a weak low pressure center. At this time it began to move across the lower Pecos River and finally lost its identity in north Texas. After it passed Del Rio, the cyclonic circulation of the storm was more distinct at 5,000 ft than at the surface. This is typical of decadent hurricanes. The storm was further identified at 5,000 ft by the temperature at the core of the disturbance which, by that time, was some 4°C colder than its surroundings. The warm anticyclone aloft and at the surface was quite strong and persistent from Florida across the Gulf Coast States into New Mexico while the storm was moving up the Rio Grande Valley. There were some weak indications in the 500-mb wind field that the storm interacted with a wave in the westerlies extending south from Montana as it was producing the record rainfall northwest of Del Rio.

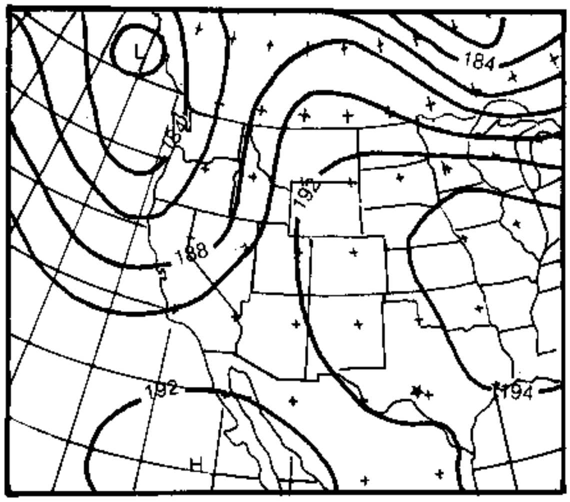
During the progress of the storm over the relatively flat country of the Rio Grande Valley below Del Rio, rains were only moderate for a hurricane. In Texas, there was a 6-in. center at Hebronville, about 130 mi northwest of Brownsville, TX, and another center in excess of 6 in. near Uvalde, about 270 mi northwest of Brownsville. Stations along the Rio Grande experienced total precipitation ranging from a fraction of an inch to 4.5 in. (fig. 2.29). In Mexico, south of the storm track, precipitation was very light. Northwest of Del Rio, some orographic effect was apparent in the reported precipitation amounts. The storm encountered the steepest slopes of the narrowing valley of the Rio Grande between the Serranias del Burro in Mexico and the tip of the Balcones Escarpment in Texas. The first of the very heavy rains, near Langtry, TX, however, began as the center of the decadent hurricane arrived there. Detailed information on the wind flow is lacking, but it is reasonable to suppose that the prevailing flow into the area of heaviest rain was from the southeast.

Several hours after the passage of the hurricane center, the rain at Langtry slacked off and stopped altogether soon after noon on the 27th. The principal activity then shifted 30-60 miles north, to the region between Pandale and Ozona, TX. A succession of thunderstorm cells released very heavy rains along this axis for as long as the center of the transforming hurricane was located a short distance to the west of the axis. The precipitation ended over this region only after the storm center moved to the north. There are two rainfall centers shown on the isohyetal analysis at which the total accumulated precipitation for the storm, according to unofficial measurements, was 35 in. The location of one (Everett) is in a saddle near the Pecos River at the head of a general slope up from the south, 1,700 ft above sea level. The other (Vic Pierce Ranch) is near a rim of a plateau at an elevation of 2,200 ft.

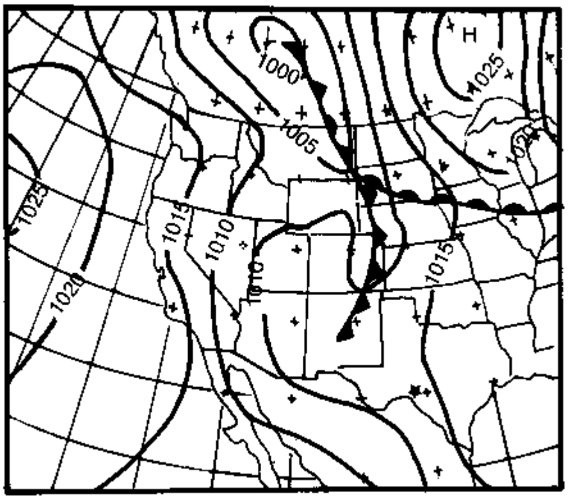
The heavy rains are most closely related to the stalling of the northwestward movement of the hurricane remnants while it was transformed into a cold-core system when interacting with a weak wave in the westerlies. Although the overall precipitation pattern can be associated with the generally southward-facing



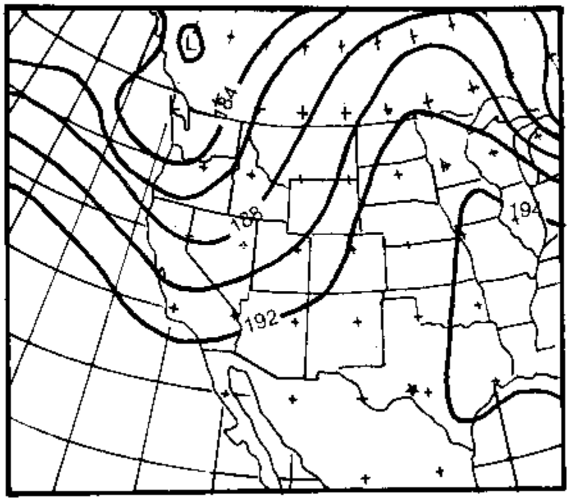
June 26 Surface 0530 MST



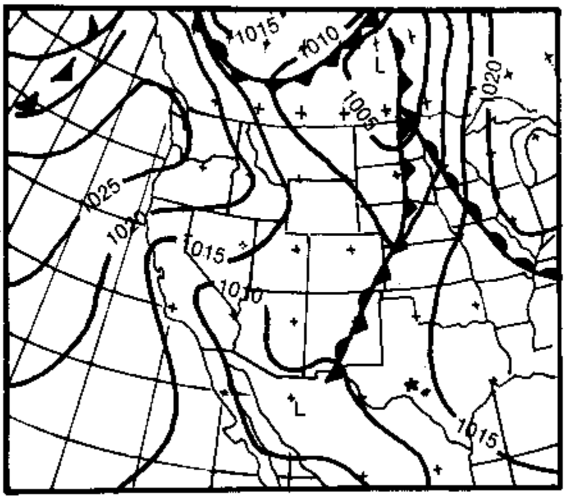
June 26 500 MB 0800 MST



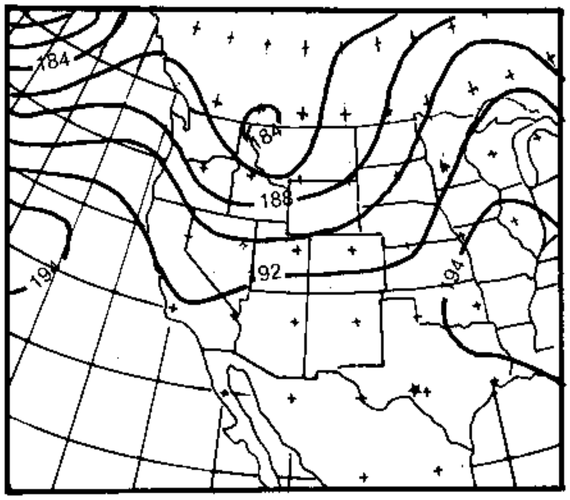
June 27 Surface 0530 MST



June 27 500 MB 0800 MST



June 28 Surface 0530 MST



June 28 500 MB 0800 MST

Figure 2.28.--Synoptic surface weather maps and 500-mb charts for June 26-28, 1954 - the Vic Pierce, TX storm (112).

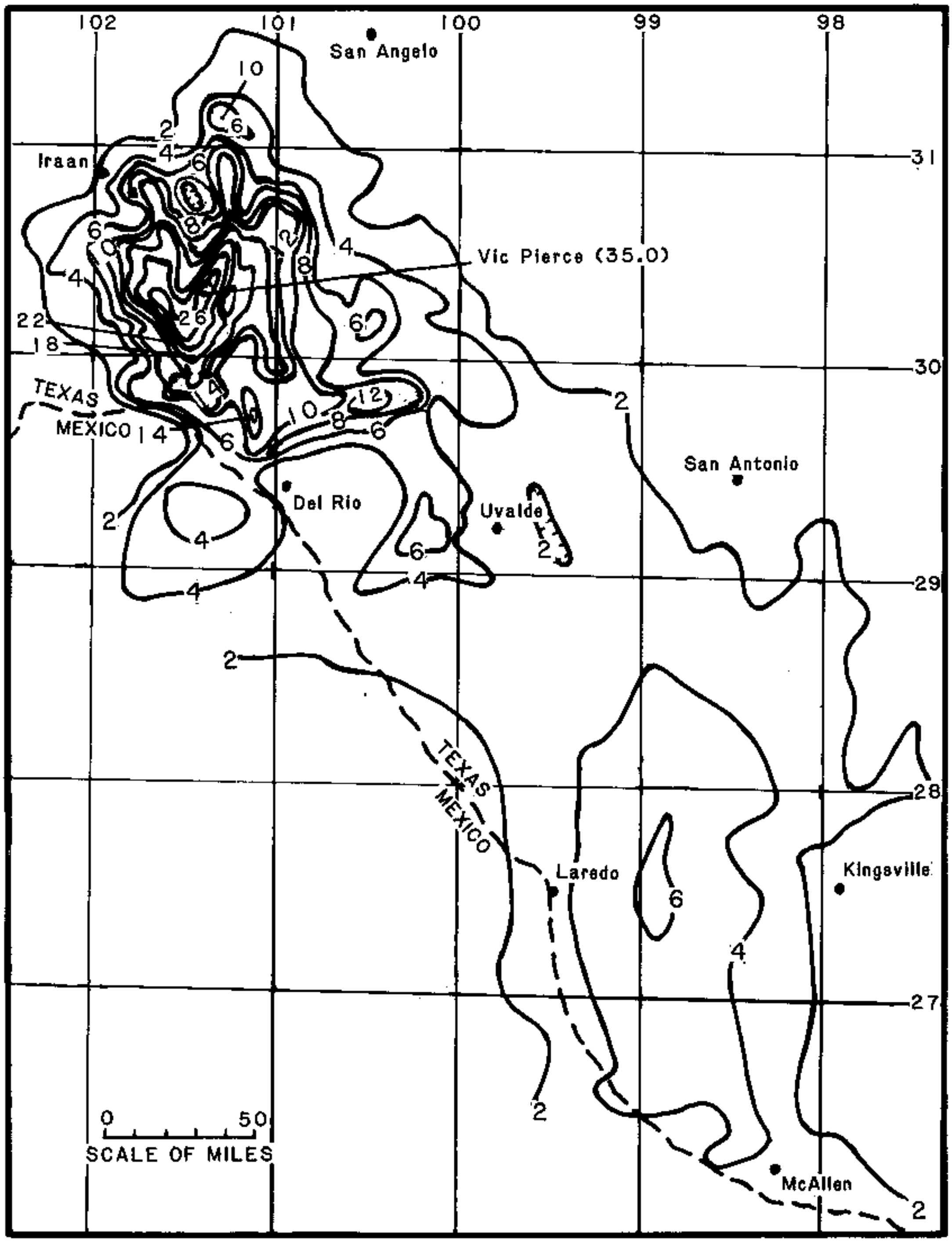


Figure 2.29.--Isohyetal map for June 24-29, 1954 - the Vic Pierce, TX storm (112).

slopes of the Edwards Plateau in the area northwest of Del Rio, specific isohyetal maxima and minima appear poorly correlated with places where the slopes are most pronounced.

2.5 Storm Classification

One objective of a comprehensive study of the meteorological situations surrounding major storms is the development of a classification or grouping system. The system may then be used to determine in which regions similar storms have occurred. Once these regions have been decided, transposition limits for individual major storms can be more easily determined. The system was developed from the study of the major rain storms in the region, some of which have been discussed in section 2.4.

2.5.1 Storm Classification System

Development of a storm classification system, based upon the factors most important for occurrence of an extreme rainfall event, is complicated by the existence of more than one factor that can be assigned in most storms. In the system developed, only one factor can be assigned to each storm. The first separation is between general cyclonic and convective storms. Within the convective storm grouping, storms are further subdivided into complex and simple systems. Within the cyclonic storm classification, the storms are grouped into tropical and extratropical storms. The extratropical storms are further classified as those in which the precipitation results primarily from frontal action and those in which the precipitation results primarily from convergence around a low pressure system.

2.5.1.1 - Characteristics of Storm Classes. Convective precipitation is caused primarily by vertical motion within an extended mass of air where the air is warmer than its environment. Convective precipitation is usually limited in areal extent and of relatively higher intensity, and produces greater amounts over smaller areas than that resulting solely from large-scale cyclonic activity. Convective storms are sometimes accompanied by thunder. Frequently in these storms, periods of intense rainfall are separated by periods of little or no precipitation. The fundamental unit is the storm cell. Diameter of this mass of air is about 10 mi or less and typically forms a single cumulonimbus cloud. The affected area is greater when a group of related convective events are considered together.

The classification system includes both simple and complex convective storms. Simple convective storms are those isolated in both time and space. The duration is usually less than 6 hr and the total storm area is generally less than 500 mi^2. When precipitation is caused by a group of simple convective storms, the event is classified as a complex convective storm. Generally the duration will be longer than 6 hr and the total storm area will be greater than 500 mi^2. It should be remembered that, in a complex convective case, the total duration of all storm events combined is less than 24 hr, and the total storm area, generally, is only a few thousand square miles.

Cyclonic precipitation is primarily caused by the large scale vertical motion associated with synoptic scale weather features such as pressure systems and fronts. The vertical motion is related to the horizontal convergence of velocity near the surface. The extent of the total storm area, as reflected by the isohyetal pattern, is typically larger than 10,000 mi^2. The total duration of the storm is one or more days. The precipitation is steady rather than high intensity bursts or showers.

The distinction between an extratropical and tropical cyclonic storm is in the location of storm origin. While extratropical storms originate at a latitude greater than 30°N, tropical storms all originate in a latitude band between 5°N and 30°N. Tropical storms affecting the CD-103 region originate in either the Gulf of Mexico, the Caribbean Sea or the Atlantic Ocean. Adequate supplies of both real and latent heat are necessary conditions for the formation of tropical storms. These conditions are met over the three tropical regions mentioned. In this study, only those storm events are included as tropical cyclones where the precipitation can be attributed to a tropical storm circulation, or where the track of the center of moisture can be matched with storms found in "Tropical Cyclones of the North Atlantic Ocean - 1871 - 1980" (Neumann et al. 1981).

Rainfall events from cyclonic storms of extratropical origin can be further subdivided into those resulting from circulation around low pressure centers and those associated with frontal systems. The rainfall associated with low pressure centers results from cyclonic flow close to the surface over an area near, and generally to the north of, the low pressure center. The low pressure center is generally moving eastward through the area of concern. The effective storm duration is generally about three days. Generally, cold fronts cause most of the extreme rainfall associated with frontal systems in this region. Such a front represents the leading edge of a mass of cooler air moving from northwest to southeast through the region. The heaviest precipitation is associated with the cold front as it passes through the region. The associated low pressure system is at least 100 mi from the precipitation center. Precipitation generally is of shorter duration than that associated with low pressure centers.

The descriptions in the previous paragraphs present idealized situations. Most storms result from a variety of causes. Since the adopted procedures allow only one classification to be assigned to each storm, a method has been developed to select the appropriate type when various causative factors are present. The storm is examined in terms of the total precipitation volume. The percentage of this volume contributed by each storm type is estimated. The storm type contributing the greatest percentage is used as the basis for storm classification. Simple convective storms cannot occur in combination, or as a portion of other storm types. In some portions of the region, these storms provide the maximum precipitation amounts for short durations and small areas. Outside these regions, combinations of convective and cyclonic types can occur. When determining the duration as discussed in the various storm types, an effective storm duration is used. This duration is defined as the shortest period of time in which at least 90 percent of the total rainfall has occurred for the majority of the storm area. This is generally determined from pertinent data sheets from "Storm Rainfall in the United States" (U.S. Army Corps of Engineers 1945 -), hereafter referred to as "Storm Rainfall." The classification of the storm type is a step-by-step process in which a decision is made on the most general categories first. A second decision follows, and for some storm types a third decision is made. The schematic for classification of storms, figure 2.30, illustrates this process.

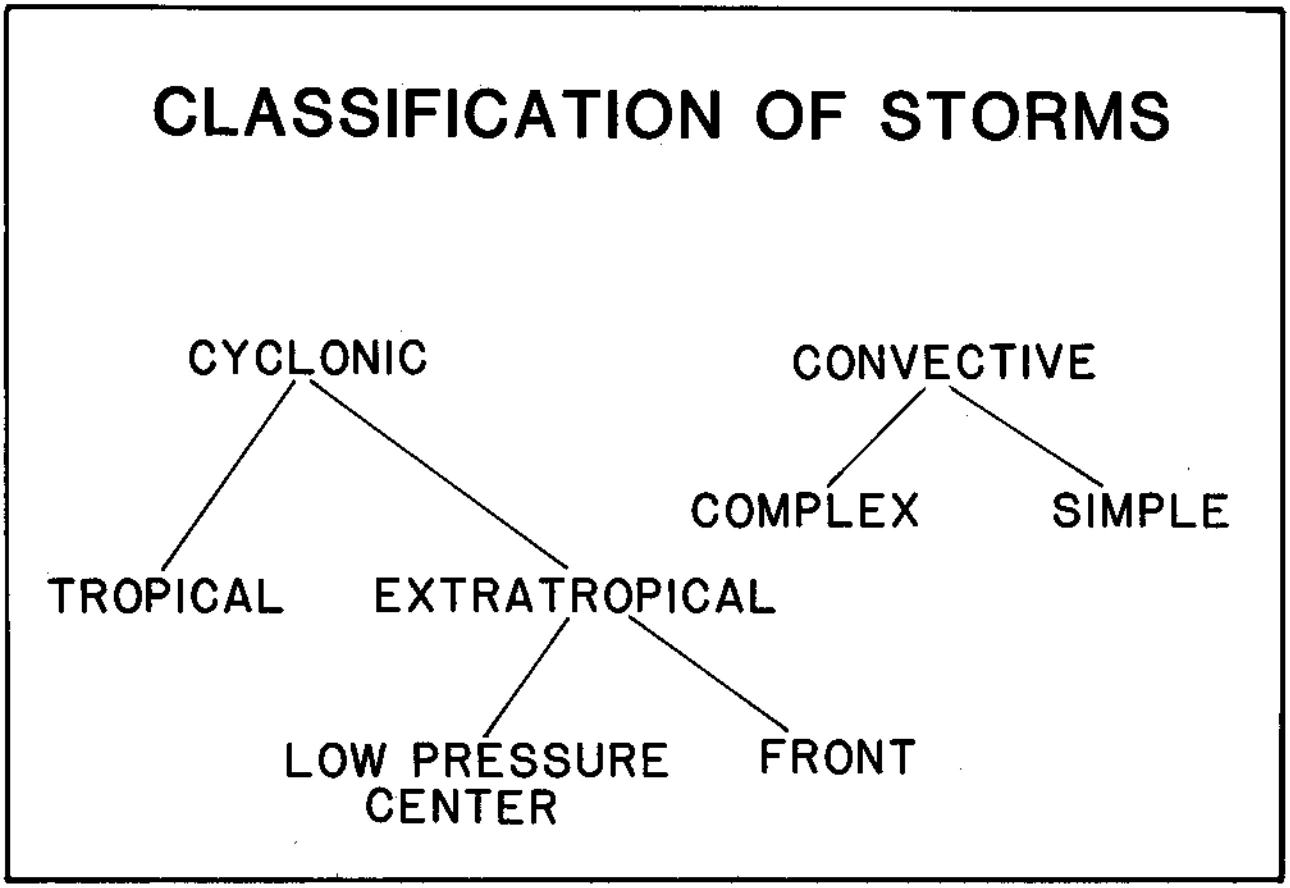


Figure 2.30.--Schematic illustrating the storm classification system.

2.5.2 Example of Application of Storm Classification System

The application of the storm classification system can be understood by examination of a particular important storm. The storm selected for this example was centered at Penrose, CO on June 2-6, 1921 (31).

2.5.2.1 Convective/Cyclonic. Five different criteria can be examined to classify a storm as cyclonic or convective. These are: 1) weather maps; 2) mass curves of rainfall; 3) isohyetal pattern; 4) effective storm duration; and 5) total storm area. An interpretive judgment will be made regarding each of these criteria.

The surface synoptic weather maps are examined for storm criteria. Figure 2.4 shows the weather maps for June 2-6, 1921. Although two cold fronts passed through the region during this storm period, one on June 1-2 and the other on June 5-6, their passage was not reflected by much rainfall. Most of the rain occurred on the night of June 3-4 at times when these fronts were at least 150 mi away. Low pressure centers were not present in the region during the period. Heavy amounts of rain were recorded at some stations, while neighboring stations observed little rain. The above features indicate that rainfall was of a convective nature.

The second criterion to examine is the mass curves of rainfall for the storm. Selected mass curves are shown in figure 2.5. These curves are examined in terms of shape and magnitude. The curves exhibit fairly short periods of intense rainfall which are separated by longer periods without rain. The spatial correlation of precipitation with distance diminishes rapidly. The rainfall also was not of a steady nature. Therefore, the criteria for mass curves indicate the storm to be a convective rainfall event.

The isohyetal pattern of the storm also provides clues to the type of rainfall event. Figure 2.5 showed an isohyetal pattern for this storm. The pattern displays a very large area of rainfall with several separate centers. These two criteria eliminate the simple convective event. The ratio of the width of the isohyetal pattern to the length is slightly less than 0.8 based on the 2-in. isohyet. Cyclonic storms tend to have isohyetal patterns which are somewhat elliptical as compared to complex convective storms, whose patterns are characterized by isolated centers, each of which is nearly circular. Rainfall between centers is not uniform and indicates the analysis could have been done in separate parts. Therefore, the isohyetal pattern for this storm is not clearly of any single group. Preponderance of evidence indicates a group within the convective class.

The effective storm duration can be determined from information provided on the pertinent data sheet in "Storm Rainfall." The total storm area, or an area size that includes at least 90 percent of the volume of storm rainfall, is used for this determination. Using the larger area sizes, the effective duration for the Penrose, CO storm is 2.5 days. This is longer than the key duration of one day for a convective storm. This criteria implies cyclonic precipitation.

The total storm area can be determined from the 2 in. isohyet on the isohyetal pattern already presented (fig. 2.5). An alternative source is the storm area information presented on the pertinent data sheet from "Storm Rainfall." For the Penrose, CO storm, the storm area from the pertinent data sheet is 144,000 mi^2. This factor also indicates a cyclonic-type storm.

Three of the five criteria considered have supported the selection of the convective group. However, the criteria should not be weighted equally. In weighting the criteria, the effects of the terrain over the region must be considered. The CD-103 region contains some areas where orography contributes to the volume of precipitation in storms. It is particularly important in considering the mass curves of rainfall and the isohyetal pattern. In the review of the Penrose, CO storm, the first three criteria should be considered more important than the final two criteria. This is considered valid even though this storm occurred over both orographic and nonorographic regions. The latter two criteria were de-emphasized because the limits for convective storms, of one day duration and 10,000-mi^2 area, should be relaxed when a group of related convective events are considered together as one storm. Clearly the mass rainfall curves demonstrate that the Penrose storm fits in this category. Additionally, no cyclonic weather system is present near the area of heavy rainfall at the time. Based on the examination of the five criteria it is concluded that the Penrose storm belongs in the convective group.

2.5.2.2 Simple/Complex. Having placed the storm in the convective group, the final decision is a choice between a complex or simple storm. The effective storm duration and total storm area were much greater than the limiting values of 6 hr and 500 mi^2 for simple convective storms. The total storm area was 144,000 mi^2. Examination of mass curves of rainfall and the isohyetal pattern indicate that the storm could have been analyzed in several sections, though each of these sections would also have exceeded the 6-hr and 500-mi^2 criteria for a simple convective storm. The Penrose storm was given a final classification as a complex convective storm.

2.5.3 Classification of Storms by Type

All important storms (table 2.2) considered in developing PMP estimates for the study region were examined and classified by storm type. Some additional storms from the more comprehensive list of major storms (table 2.1) were also classified by storm type to aid in the initial determination of storm transposition limits. The storms are listed in table 2.3, grouped by appropriate storm type. Within each storm type, the storms where orography played a significant role in the precipitation process are grouped separately from those where orography

Table 2.3.--List of storms of record considered for CD-103 region by storm type

Storm number	Name	Date
	Low Pressure System	(Orographic)
1.	Ward District, CO	May 29-31, 1894
3.	Big Timber, MT	April 22-24, 1900
6.	Boxelder, CO	May 1-3, 1904
7.	Spearfish, SD	June 2-5, 1904
10.	Warrick, MT	June 6-8, 1906
12.	Choteau, MT	June 21-23, 1907
13.	Evans, MT	June 3-6, 1908
14.	Norris, MT	May 22-24, 1909
19.	Ft. Union, NM	June 6-12, 1913
28.	Browning, MT	September 27-28, 1919
30.	Fry's Ranch, CO	April 14-16, 1921
36.	Hays, MT	June 16-21, 1923
45.	Westcliffe, CO	April 19-22, 1933
50.	Circle, MT	June 11-13, 1937
52.	Big Timber, MT	May 17-20, 1938
68.	Dupuyer, MT	June 16-17, 1948
71.	Belt, MT	June 1-4, 1953
75.	Gibson Dam, MT	June 6-8, 1964
79.	Broomfield, CO	May 5-6, 1973
	Low Pressure System	(Least Orographic)
86.	May Valley, CO	October 18-19, 1908
16.	Knobles Ranch, MT	September 3-6, 1911
20.	Clayton, NM	April 29-May 2, 1914
32.	Springbrook, MT	June 17-21, 1921
38.	Savageton, WY	September 27-Oct. 1, 1923
58.	McColleum Ranch, NM	September 20-23, 1941
61.	Dooley, MT	March 13-17, 1943

Table 2.3.--List of storms of record considered for CD-103 region by storm type - (continued)

Storm number	Name	Date
	Cold Front	(Orographic)
8.	Rociada, NM	September 26-30, 1904
23.	Tajique, NM	July 19-28, 1915
33.	Denver, CO	August 17-25, 1921
35.	Virsylvia, NM	August 17, 1922
37.	Sheridan, WY	July 22-26, 1923
57.	Campbell Farm Camp, MT	September 6-8, 1941
59.	Tularosa, NM	September 27-29, 1941
77.	Big Elk Meadow, CO	May 4-8, 1969
	Cold Front	(Least Orographic)
15.	Half Moon Pass, MT	June 7-8, 1910
25.	Lakewood, NM	August 7-8, 1916
44.	Porter, NM	October 9-12, 1930
56.	Prairieview, NM	May 20-25, 1941
62.	Colony, WY	June 2-5, 1944
	Tropical Cyclone	(Orographic)
27.	Meek, NM	September 15-17, 1919
60.	Rancho Grande, NM	Aug. 29-Sept. 1, 1942
	Tropical Cyclone	(Least Orographic)
105.	Broome, TX	September 14-18, 1936
112.	Vic Pierce, TX	June 23-28, 1954
116.	Medina, TX	August 1-4, 1978
117.	Albany, TX	August 1-4, 1978
	Complex Convective	(Orographic)
11.	Ft. Meade, SD	June 12-13, 1907
29.	Vale, SD	May 9-12, 1920
31.	Penrose, CO	June 2-6, 1921
41.	Cheesman, CO	July 19-24, 1929
46.	Kassler, CO	September 9-11, 1933
53.	Loveland, CO	Aug. 30-Sept. 4, 1938
54.	Waterdale, CO	Aug. 31-Sept. 4, 1938
66.	Ft. Collins, CO	May 30, 1948
78.	Rapid City, SD	June 9, 1972
81.	Big Thompson, CO	July 31-Aug. 1, 1976
	Complex Convective	(Least Orographic)
21.	Malta, MT	June 12-14, 1914
40.	Beach, ND	June 6-7, 1929
42.	Valmora, NM	August 6-11, 1929
43.	Gallinas Plant Station, NM	September 20-23, 1929

Table 2.3.--List of storms of record considered for CD-103 region by storm type - (continued)

Storm number	Name	Date
47.	Cherry Creek, CO	May 30-31, 1935
101.	Hale, CO	May 30-31, 1935
49.	Ragland, NM	May 26-30, 1937
108.	Snyder, TX	June 19-20, 1939
111.	Del Rio, TX	June 23-24, 1948
72.	Buffalo Gap, Sask.	May-30, 1961
73.	Lafleche Sask	June 12-13, 1962
74.	Bracken, Sask	July 13-14, 1962
76.	Plum Creek, CO	June 13-20, 1965
114.	Glen Ullin, ND	June 24, 1966
82.	White Sands, NM	August 19, 1978
	Simple Convective	(Orographic)
48.	Las Cruces, NM	August 29-30, 1935
67.	Golden, CO	June 7, 1948
	Simple Convective	(Least Orographic)
55.	Masonville, CO	September 10, 1938

played a minimal role. The simple convective storms listed at the end of the table are among those which are considered appropriate for use in determining local storm criteria. Development of the local storm criteria is discussed more completely in chapter 12. The locations of the important storms (table 2.2) for determining PMP, identified by appropriate storm type, are shown in figure 2.31.

Tracks of tropical storms listed in table 2.4, are shown in figure 2.32. The tracks are composed of two segments. Solid lines are tracks extracted from Neumann et al. (1981), and dashed line segments are extrapolated using either surface weather observations at 0600 or from reported precipitation amounts. The

Table 2.4.--Dates of tropical storms affecting southern portion of CD-103 region

From Neumann et al. (1981)	Plotted in figure 2.32	From Neumann et al. (1981)	Plotted in figure 2.32
7/13-22/09	7/21-26/09	9/10-14/36	9/13-14/36
8/20-28/09	-	9/11-16/41	-
6/22-28/13	6/27-28/13	8/21-31/42	8/29-9/1/42
8/12-19/16	8/18-21/16	8/24-29/45	8/27-31/45
9/12-15/19	9/14-18/19	7/31-8/2/47	-
6/12-16/22	-	6/24-26/54	6/25-28/54
9/6-7/25	-	6/14-16/58	6/15-16/58
6/26-29/29	6/28-7/1/29	7/22-27/59	-
8/11-14/32	-	8/5-8/64	-
7/21-26/34	-	7/30-8/5/70	8/3-5/70

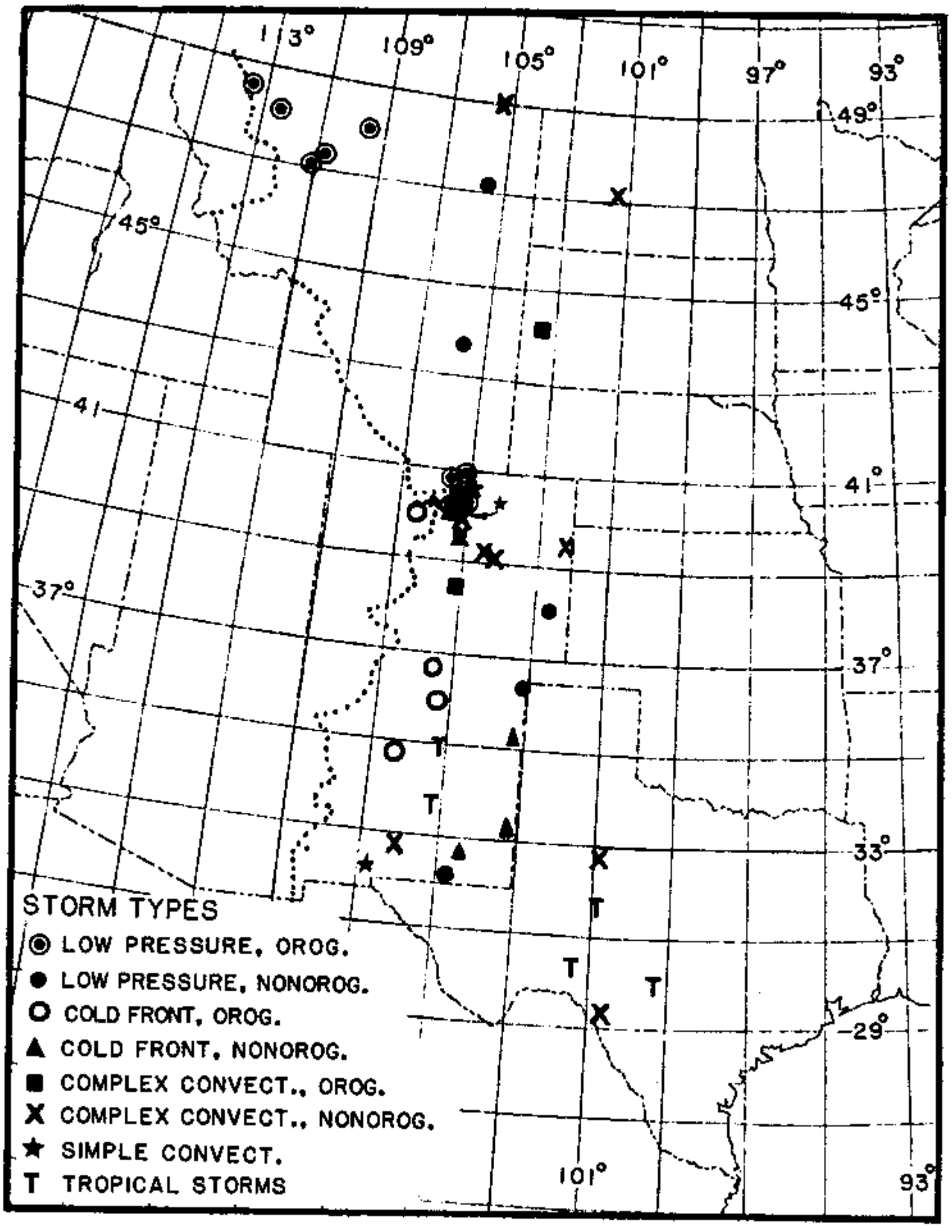


Figure 2.31.--Location of table 2.2 storms by storm type.

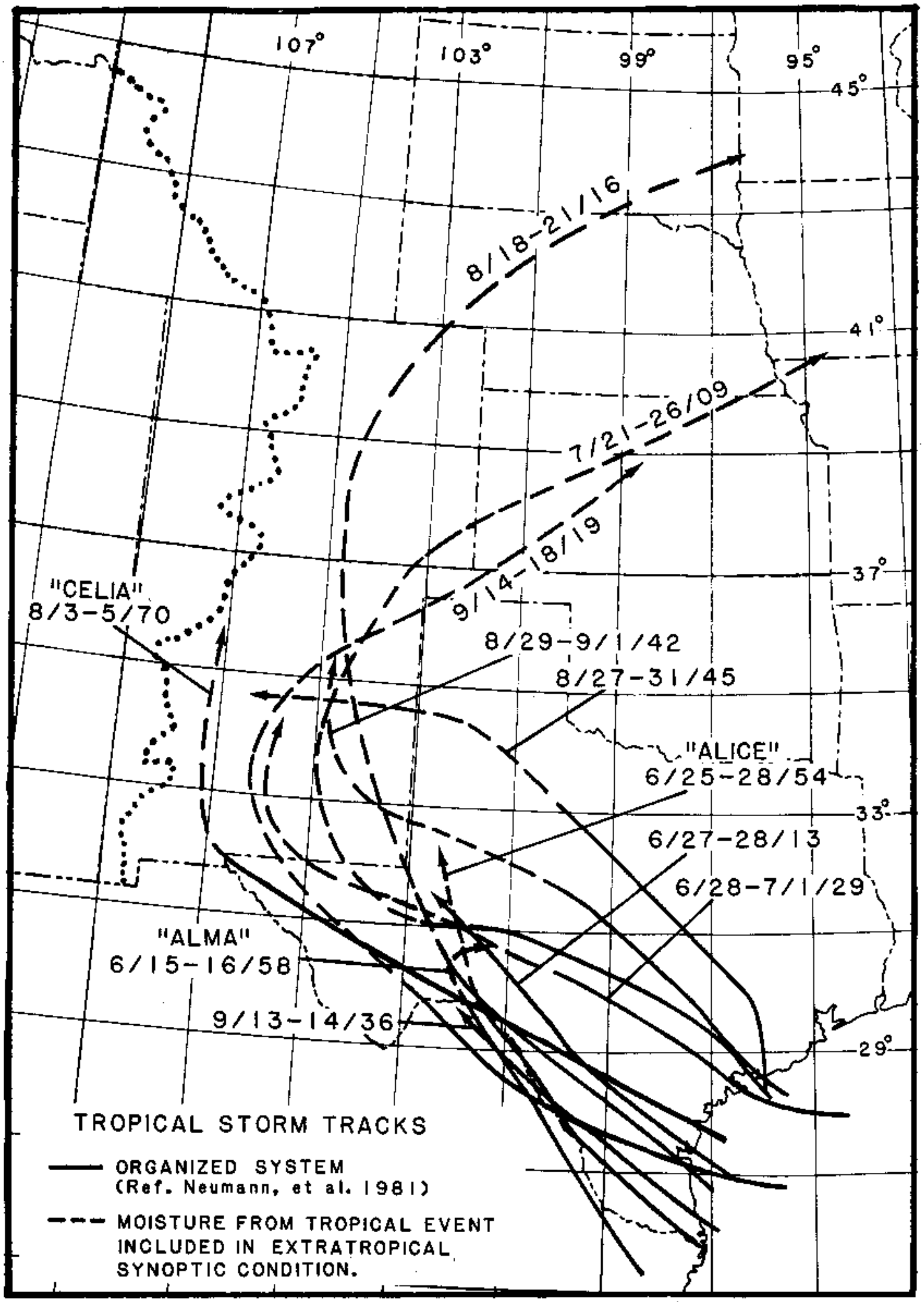


Figure 2.32.--Tracks of tropical storms affecting the southern part of CD-103 region.

precipitation was typically an accumulation over a 3-day time span, but could be for a period as short as 24 hr, or for as long as 6 days. Precipitation was always clearly associated with the tropical storm. Where possible, rainfall maxima were determined near the coast, the east-central region and the western third of Texas, to provide some idea of the change of potential rainfall for a storm.

3. TERRAIN CLASSIFICATION SYSTEM

3.1 Introduction

At the onset of the CD-103 study, it was recognized that terrain within the region was extremely complex. It was useful, therefore, to subdivide the region according to some classification system. This would allow for consideration of different approaches to developing PMP within different subdivisions that might have varying degrees of orographic effects, or aid in defining storm transposition limits.

3.2 Classification

The terrain classification system that evolved recognized several different types of terrain influence. Of most importance was the separation into orographic and nonorographic regions. Within the orographic region, it was important to recognize the differences in effect of first and second upslopes.

3.2.1 Orographic/Nonorographic Line

First, it was necessary to develop a division between orographic and non-orographic regions. The Great Plains region is a relatively flat region with elevations generally increasing to the north and west. In HMR No. 51, a gentle upslope correction was applied to account for the loss of moisture at higher elevations. In the present study, this factor is considered in the moisture adjustment procedure. Within this region, there are no prominent orographic features which would stimulate or enhance precipitation in a storm of the magnitude of the PMP. This region is considered nonorographic in the study. Exactly how far westward this nonorographic region should extend is subject to question, although the Rocky Mountains are certainly orographic. The influence of orography on moist air inflow from the Gulf of Mexico was chosen as the key criteria. Inflow winds would be essentially from the east and would be minimally affected by terrain until they encountered the first upslopes in the CD-103 region. Upslopes in this study were represented by changes in elevation greater or equal to 1,000 ft in 5 mi or less. A smooth line was drawn connecting locations that satisfied the base level of this gradient.

Second, orographic stimulation is a term applied when the effects of terrain influence on the atmosphere in producing precipitation appear at some distance upwind of any actual terrain feature. In this sense, the effect occurs in what could be considered a nonorographic environment. The distance over which such effects occur is not well known since they are influenced by the steepness of the slope, height and lateral extent of the barrier and direction of inflow wind in major storms against the barrier. A distance of about 20 mi was considered reasonable to represent the extension of orographic influence into surrounding nonorographic terrain. Stimulation was also considered in HMR No. 43 where it was applied to the regions west of the Cascade Divide. Distance intervals used in HMR No. 43 are larger than in the present study, because of generally stronger winds within more stable air in that region.

As a result of stimulation considerations, another smooth enveloping line was drawn from the Canadian border to the Mexican border, roughly 20 mi east of the base of the first upslopes, and this line was eventually adopted as representing a logical division between orographic and nonorographic regions. The adopted location of the orographic separation line (OSL) is shown in figure 3.1. An additional orographic subdivision was necessary in Montana to delineate the orographic region enclosing the Bear Paw Mountains. Another subdivision of similar nature was drawn around the Black Hills in South Dakota.

It should be noted that in following the rather simple guidelines for locating the orographic separation line, placement was somewhat obvious through Montana and Colorado. In Wyoming, however, placement is not always as clear. This is especially the case in the central part of the state where no notably steep slopes occur and the flow is more along the barriers than normal to them. In this region, the outline of the Wind River Valley (fig. 3.1) was followed.

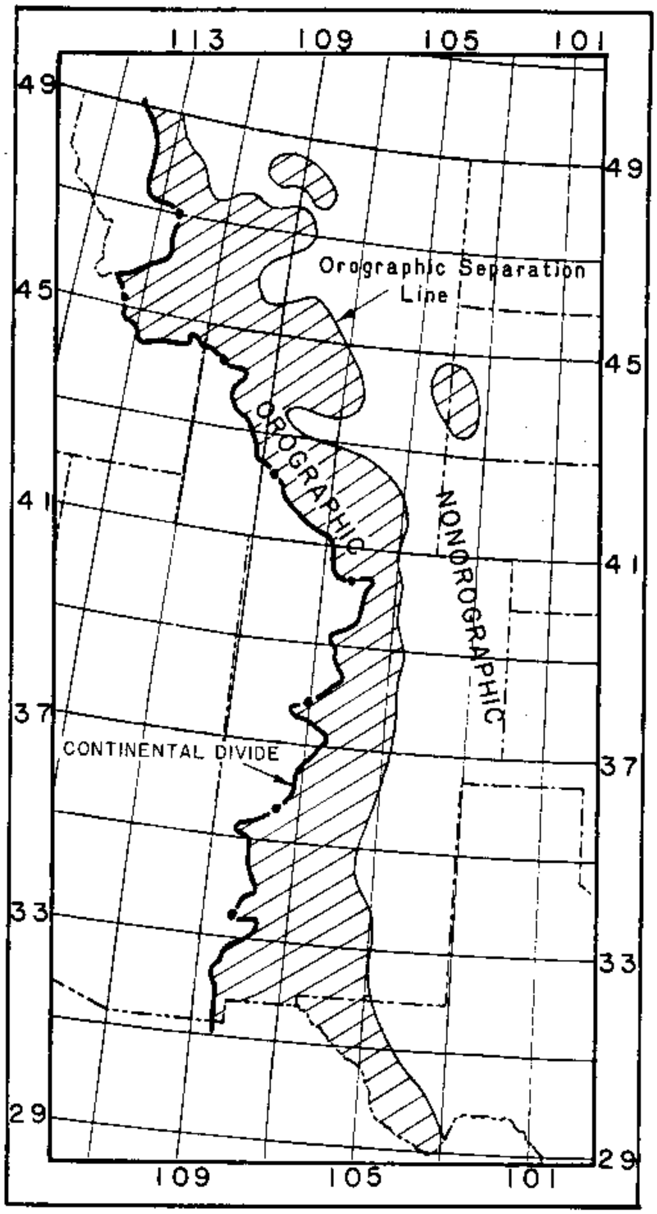


Figure 3.1.--Study region showing line separating orographic and nonorographic regions (orographic separation line - OSL).

3.2.2 First Upslopes

After separating the broadscale orographic/nonorographic regions, the orographic region was examined for possible further subdivision. One readily apparent subregion was the first upslopes. When considering the flow of moist air in passing over such terrain, the first upslopes generally have the greatest effect in producing precipitation. The secondary upslopes, behind the first upslopes, are effective in producing precipitation only to the extent that they rise higher than the first upslopes, or that the air can descend and be lifted again when encountering the second slopes.

Terrain maps were again analyzed to designate the limit of first upslopes. A broadscale consideration was to place this limit at the Continental Divide, unless multiple ridgelines occurred upwind. The dashed line in figure 3.2 shows the result of these considerations. It should be emphasized that this separation was based on major crests, not minor interruptions to a general upslope. The portion to the east of this dashed line in the CD-103 region is referred to as the first upslope subdivision, while the region west of this line contains secondary orographic slopes. Particularly in Wyoming, the placement of the dashed line was poorly defined by the terrain. A number of choices were possible and the selection shown in figure 3.2 was considered to be the most logical.

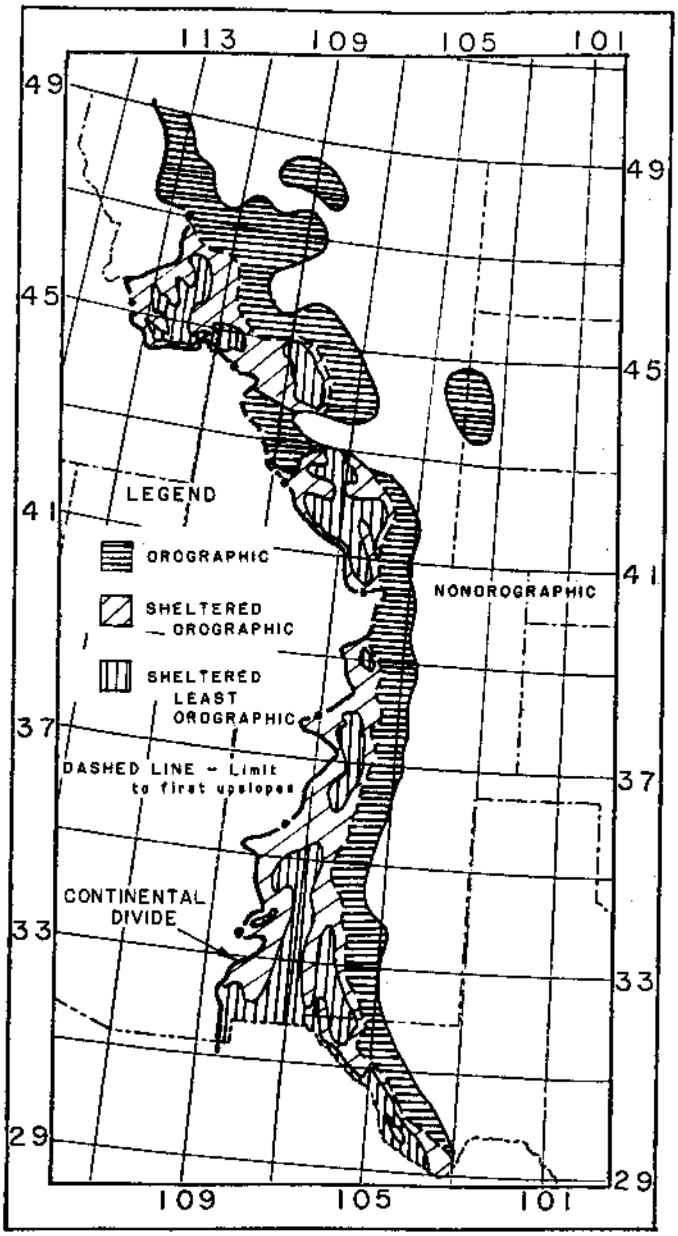


Figure 3.2.--Approximate boundaries of terrain subdivisions used in this study.

3.2.3 Sheltered Least Orographic Subdivisions

For much of Wyoming and some parts of Montana, Colorado and New Mexico, it was apparent that there would be subdivisions of sheltered conditions to the west of the first upslope subdivision. As an approach to locating such subdivisions, the horizontal gradient of terrain was considered. A tentative sheltered least orographic subdivision was designated when the terrain gradient was essentially flat over a distance exceeding 10 mi, to the west of the first upslope subdivision. It was further examined on the basis of the apparent effect the terrain gradient (upslope) had on the 100-yr 24-hr precipitation. The subdivisions tentatively designated sheltered least orographic were found to be somewhat consistent with zones having less than or equal to 3.0 in. of 100-yr 24-hr precipitation (Miller et al. 1973). On this basis, portions of the CD-103 region, where the 100-yr 24-hr precipitation was less than or equal to 3.0 in., and located west of the limit of the first upslopes, were designated as sheltered least orographic. An exception to this apparent agreement occurs in New Mexico, south of about 36°N, where 100-yr 24-hr precipitation is generally greater than 3.0 in. Nevertheless, a sheltered least orographic subdivision was designated in southern New Mexico (fig. 3.2). This decision was in part a result of observations made during the aerial reconnaissance of this region (sec. 1.6).

3.2.4 Sheltered Orographic Subdivisions

The region between the sheltered least orographic subdivision and the orographic subdivision boundary line (limit of the first upslopes) was designated as sheltered orographic. These sheltered orographic slopes exert less influence on moisture flows than do similar slopes in the orographic subdivision.

3.3 Barrier/Effective Elevation Map

It is customary when discussing moist air flow in orographic terrain to consider the effect of the terrain on the moisture. One of the primary effects is that in passing over a major ridgeline, saturated air will lose moisture through precipitation. Thus, when considering conditions in the lee of major ridges, the moisture potential is reduced. In hydrometeorological applications, it is assumed that 100 percent of the moisture available beneath the height of the ridge is lost by the air passing across the ridge. Thus, the ridge is referred to as a barrier.

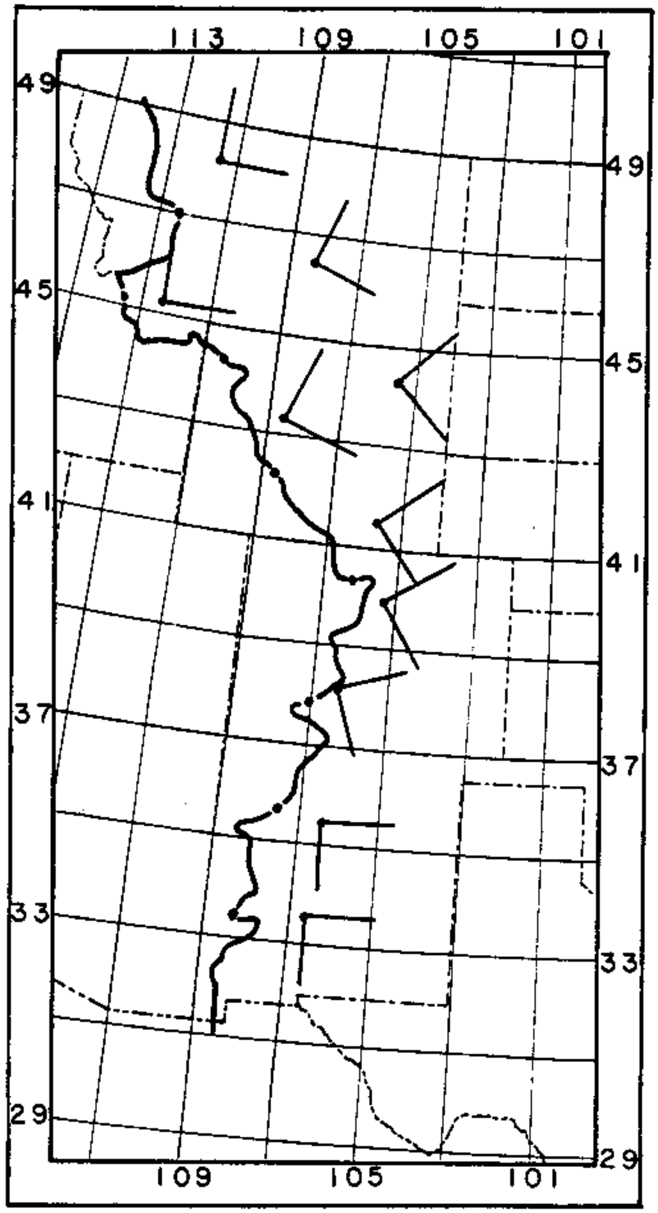


Figure 3.3.--Range of inflow wind directions for PMP type storm.

To determine where such barriers exist in the CD-103 region, the inflow directions that would prevail in PMP-type storms were considered. It was assumed that such storms can be approximated by major storms of record, and the mean winds for such storms in the CD-103 region were evaluated. In the southern portion of the region, moist inflows are southerly. In the northern portion of the region, moisture inflow to some storms appears to have a northerly component. Reference to the discussion of major storms (chapt. 2) clarifies this situation.

Inflow directions can be represented by a range of roughly 90 degrees throughout the study region. Figure 3.3 shows the results of the review of inflow directions to major storms. A gradual variation from southerly to easterly to northerly directions with increasing latitude has been smoothed into the results shown.

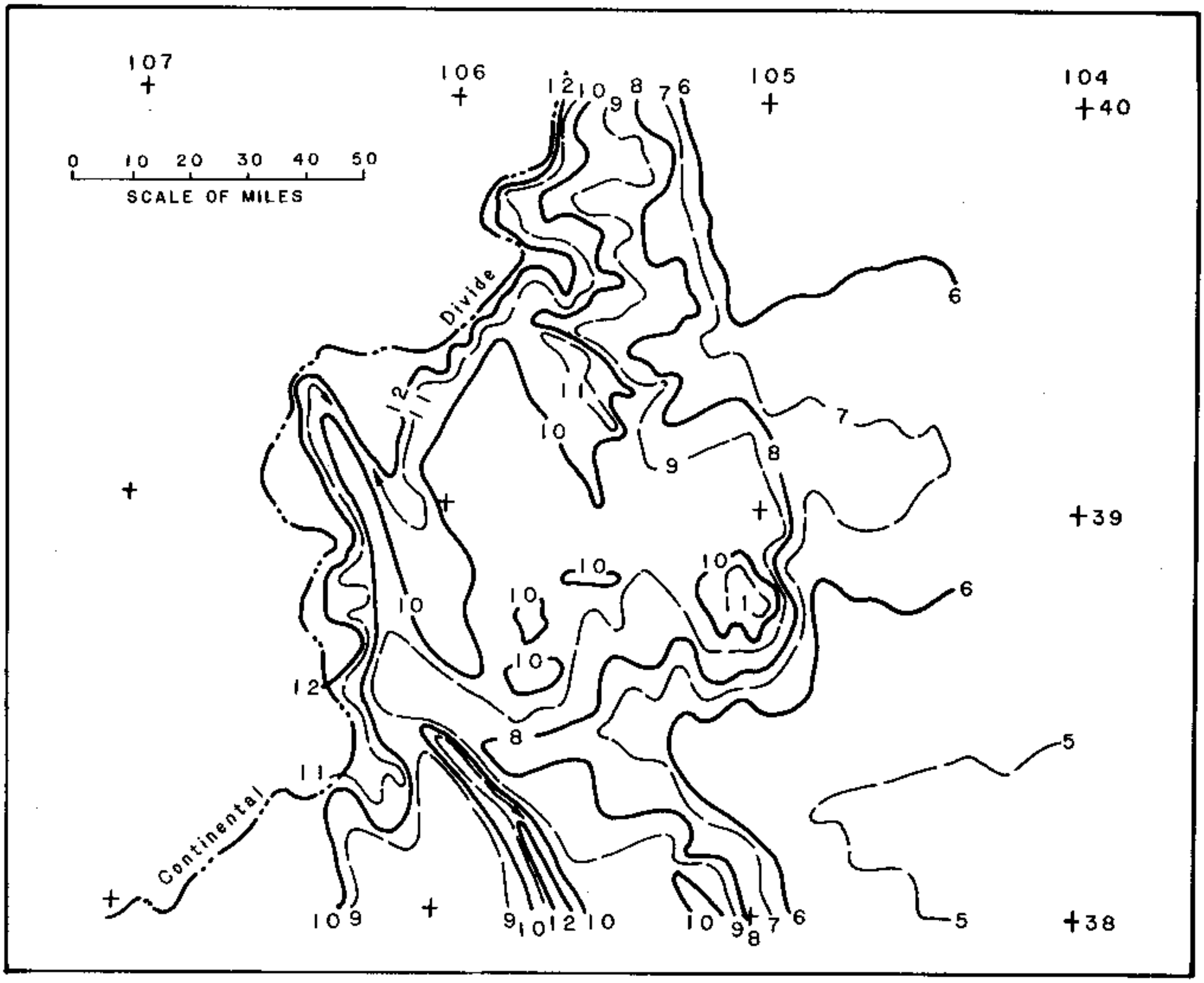


Figure 3.4.—Barrier/smoothed elevation map (in 1,000's of ft) for a 2° latitude band (38° to 40°N) through Colorado.

The next step was to consider terrain elevations. It was impractical to consider the detail in elevation contours found on maps of the scale of 1:250,000, or less. A map scale of 1:1,000,000 was chosen for a basic work chart. Contours of elevation had previously been extracted, with a small degree of smoothing, for the development of NOAA Atlas 2 (Miller et al. 1973). These contour maps were used as the first approximation to the base maps in this study. Some additional smoothing was made to the NOAA Atlas 2 elevation contours by eliminating topographic features on the order of 10 mi or less. The degree of smoothing decreased, however, as elevation increases.

A barrier map was prepared by considering inflow directions and their affect on air encountering the smoothed elevation contours. In the atmosphere, air not only flows over ridges, it flows also around the ends of such obstacles. Therefore, it is necessary to judge how moist air flow affects the region behind a barrier. This consideration is important primarily for smaller barriers (order of less than 100 mi in breadth). In such situations, the rule applied in the HMR No. 49 study was used in this study. This rule states that airflow around these obstacles would be brought together on the leeside of the obstacle at a distance 1.5 times the breadth of the barrier.

With these considerations in mind, the entire CD-103 region was analyzed to produce a barrier/effective elevation map. Because of the difficulty in showing detail at page-size scale, only a portion of the map for Colorado has been shown in figure 3.4, as an example. Elevation ranges of meteorologically significant barriers are between 4,000 and 12,000 ft in Colorado. The flow can be perpendicular as well as parallel, to the ridge lines. This is particularly true in New Mexico. Where this is true, ridges were considered ineffective as barriers.

4. MAXIMUM PERSISTING 12-HR 1000-MB DEW POINTS

4.1 Background

The basic steps leading to precipitation are: (1) sufficient atmospheric moisture, (2) cooling of the air, (3) condensation of water vapor into liquid or solid form, and (4) growth of condensation products to precipitation size. The measure of water vapor in the air used in hydrometeorological studies is precipitable water. Two measures of moisture are needed in PMP studies; the amount in individual storms and the maximum amount that can occur. Since the precipitable water measurements are not directly available prior to the 1940's and since even the current measurements do not always provide an adequate geographic coverage, a surface measurement of moisture has been used. Dew-point data were selected for use since they are: 1) good measures of moisture in storm situations, (particularly in the lowest layers), 2) observed at a dense network of stations, and 3) available for a long period of record.

Maximum persisting 12-hr 1000-mb dew points are used as a measure of the maximum precipitable water that can be expected in various regions of the United States in various months. The initial dew-point study was completed in the early 1940's. For the western United States, maximum persisting 12-hr 1000-mb dew points for individual stations for durations from 12 to 96 hr were published in Weather Bureau Technical Paper No. 5, "Maximum Persisting Dew Points in the Western United States," (U.S. Weather Bureau 1948). Subsequently, maps of maximum persisting 12-hr dew points for the entire United States were published in the "Climatic Atlas of the United States" (Environmental Data Services 1968). For most of the United States, the maps were based on records from selected Weather Bureau first order stations from the beginning of observations to 1946. For New York and New England, they were updated using data through 1952 with some consideration given to maximum sea-surface temperatures in shaping the dew-point lines. For California, updated maps were prepared using data through 1958 for the months of October through April, when PMP studies were done for that region (U.S. Weather Bureau 1961). In subsequent studies, the maps of maximum persisting dew points were updated for the Pacific Northwest (U.S. Weather Bureau 1966) and the Colorado River and Great Basin in Hydrometeorological Report No. 50, "Meteorology of Important Rainstorms in the Colorado River and Great Basin Drainages" (Hansen and Schwarz 1981).

For the present study, it was considered desirable to update the maps appearing in the Climatic Atlas of the United States. Moisture flow for the major storms in this region primarily originates over the Gulf of Mexico and moves northward across the midwestern portion of the country. Thus, surface dew points were examined for stations in the central portion of the United States.

Table 4.1.--Stations used in revision of maximum persisting 12-hr 1000-mb dew-point charts

1.	Aberdeen, SD	41.	Kansas City, MO
2.	Abilene, TX	42.	Lander, WY
3.	Alamosa, CO	43.	Lewistown, MT
4.	Albuquerque, NM	44.	Little Rock, AR
5.	Alexandria, LA	45.	Lubbock, TX
6.	Amarillo, TX	46.	Mason City, IA
7.	Austin, TX	47.	Midland, TX
8.	Billings, MT	48.	Miles City, MT
9.	Bismarck, ND	49.	Minot, ND
10.	Brownsville, TX	50.	Missoula, MT
11.	Casper, WY	51.	Norfolk, NE
12.	Cheyenne, WY	52.	North Platte, NE
13.	Clayton, NM	53.	Oklahoma City, OK
14.	Columbia, MO	54.	Omaha, NE
15.	Colorado Springs, CO	55.	Port Arthur, TX
16.	Concordia, KS	56.	Pierre, SD
17.	Corpus Christi, TX	57.	Pueblo, CO
18.	Cut Bank, MT	58.	Rapid City, SD
19.	Dallas, TX	59.	Rock Springs, WY
20.	Del Rio, TX	60.	Roswell, NM
21.	Denver, CO	61.	Roswell, Walker AFB, NM
22.	Dillon, MT	62.	Salina, KS
23.	Dodge City, KS	63.	San Angelo, TX
24.	Eagle, CO	64.	San Antonio, TX
25.	El Paso, TX	65.	Scottsbluff, NE
26.	Enid, OK	66.	Sheridan, WY
27.	Fargo, ND	67.	Shreveport, LA
28.	Fort Smith, AR	68.	Sioux City, IA
29.	Galveston, TX	69.	Sioux Falls, SD
30.	Glasgow, MT	70.	Spokane, WA
31.	Goodland, KS	71.	Springfield, MO
32.	Grand Forks, ND	72.	St. Joseph, MO
33.	Grand Island, NE	73.	St. Louis, MO
34.	Grand Junction, CO	74.	Topeka, KS
35.	Great Falls, MT	75.	Tulsa, OK
36.	Havre, MT	76.	Vichy, MO
37.	Helena, MT	77.	Victoria, TX
38.	Huron, SD	78.	Waco, TX
39.	Houston, TX	79.	Wichita, KS
40.	Kalispell, MT	80.	Wichita Falls, TX
		81.	Williston, ND

4.2 Data Collection

The basic data for this part of the study were obtained from the synoptic weather reports for 74 stations between the 94th meridian and the Continental Divide and 7 stations west of the Continental Divide. The 81 stations are listed in table 4.1 and their locations are shown in figure 4.1. Data for these

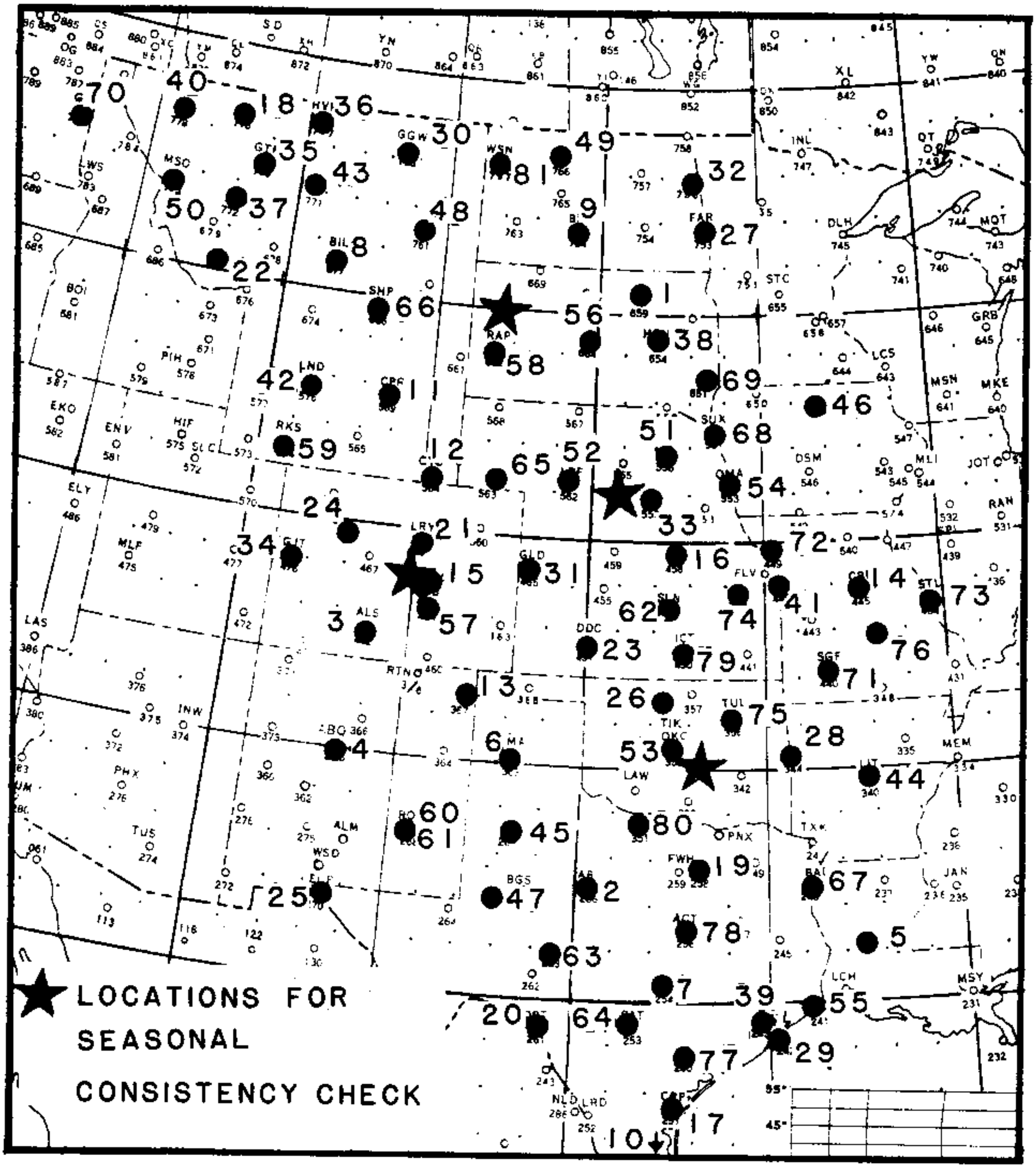


Figure 4.1.--Location of weather stations used to revise maximum persisting 12-hr 1000-mb dew points.

stations are available on a series of computer data tapes (Peck et al. 1977) maintained by the Office of Hydrology.

The first step in collecting the data was to determine current seasonal variation of maximum persisting 12-hr dew points at each of these stations. For this purpose, the mid-month value was determined for each station for each month from the existing maps of maximum persisting 12-hr 1000-mb dew points (Environmental Data Service 1968). The values were adjusted to the station elevation by the pseudoadiabatic lapse rate, approximately -2.4°F per 1,000 ft, and a seasonal variation curve drawn for each station. From these curves, the minimum value was determined for each station for each month and established as a threshold value. This dew point was the lowest value along the seasonal variation curve and occurred on either the first or last of the month. For example (fig. 4.2), for Roswell, NM a value of 55°F was determined for the station dew-point value for the first of April.

Thirty-one years of data, from 1948 through 1978, on the data tapes were searched with additional checks made for known instances of significant precipitation and moisture through 1981. For each station, those 12-hr periods were listed where the dew point continually equalled or exceeded the threshold value for a particular month. Since the data were at 3-hr intervals, this meant the lowest dew point of five consecutive values was used as the maximum persisting 12-hr value. Minimum temperatures were checked to insure the temperature did not fall below the selected dew point between observation times. If more than one of the five reports was missing the series was rejected. All values which exceeded the smooth seasonal curve by more than 2°F for each station, listed in table 4.2, for the date of occurrence, were verified. The first check of the values was to examine the values published in the Local Climatological Data (National Climatic Data Center 1948 -) to insure that correct values had been entered on the data tape. A second and more significant check was made with the Historical Daily Weather Maps (Environmental Data Service 1899-1971) for the date of occurrence. Maximum persisting 12-hr dew points are assumed to be representative of storm conditions. The general weather situations were examined to insure that they were favorable for supporting high moisture that could contribute to large precipitation amounts.

4.3 Analysis

New seasonal curves were prepared for each station. Figure 4.2 shows an example of such a curve. In the example, the values which exceed the previous curve are shown by the small squares and the revision to the existing seasonal curve is shown by the dashed line. In developing these analyses, consideration was given to data at surrounding stations, while still attempting to maintain a minimum envelopment of the individual station data. The next step was to read the values at mid-month for each station for each month. These values were then plotted on the original dew-point charts and the isolines redrawn for the new seasonal mid-month values.

After the maps for all 12 months were completed it was necessary to insure that regional and seasonal consistency was maintained. Seasonal curves were drawn at 4-degree intervals of latitude along the 97th, 101st, 103rd, 105th and 109th meridians, and at selective points along the Continental Divide and throughout the region. Figure 4.3 shows an example of these curves along the 103rd meridian for 31, 35, 39, 43 and 47 degrees latitude. The dashed lines are the results of the initial analysis. The curves along the meridians were then used to adjust and modify the initial analysis into a consistent set of regional and seasonal curves. The revisions are shown as the solid lines on figure 4.3. Where only dashed lines are shown, the initial analysis did not require further smoothing. The final step was to compare the mid-month values from the revised maps with the data on the original set of station seasonal curves. These mid-month values are

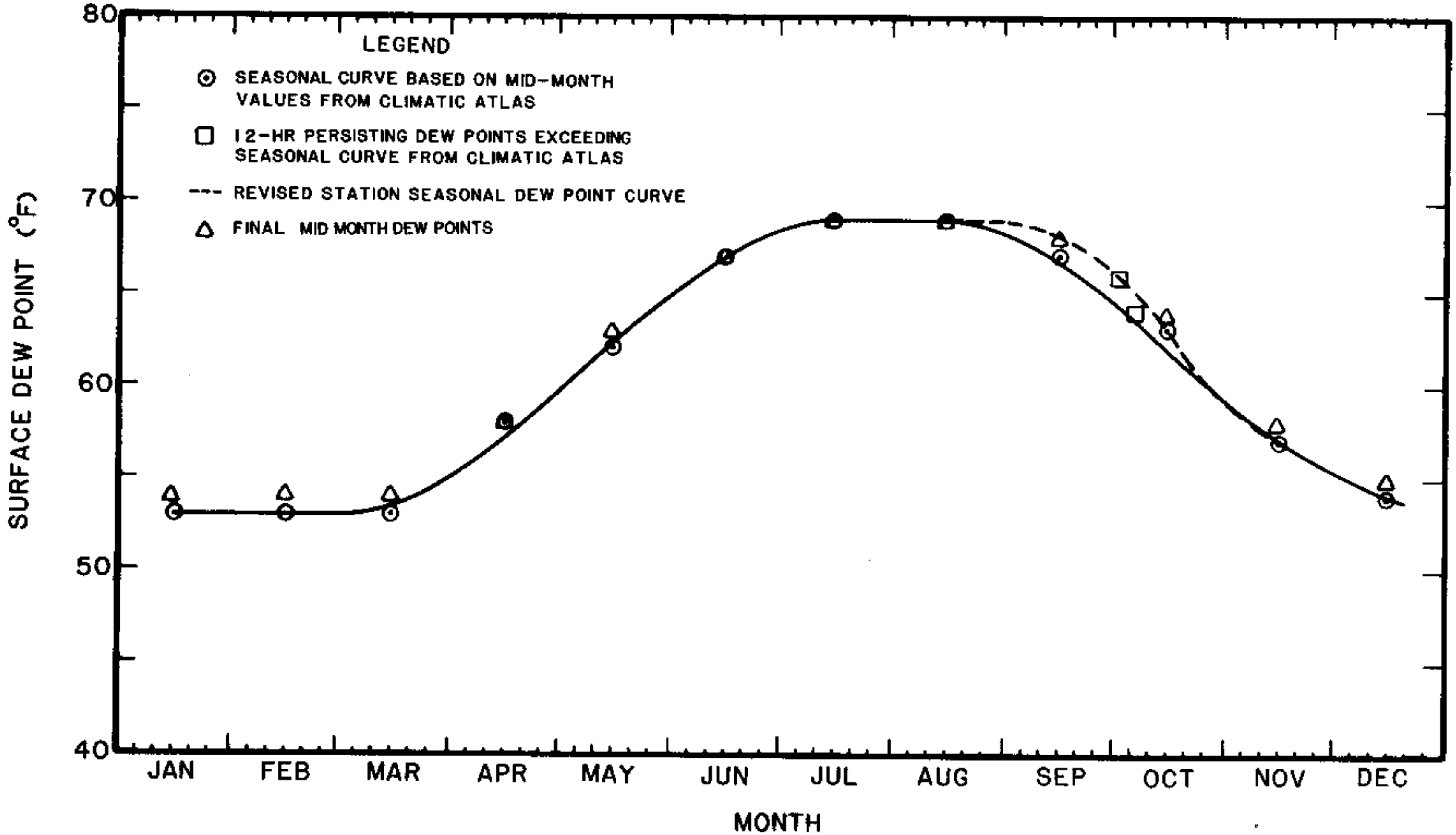


Figure 4.2.--Seasonal persisting 12-hr dew-point curve for Roswell, NM (Walker AFB).

Table 4.2.--Persisting 12-hr dew points 2°F or more above existing criteria on date of occurrence

Station	Date of Occurrence	Station dew point
Sioux City, IA	July 12, 1969	79°
	July 19, 1966	77°
Vichy, MO	Aug. 20, 1952	78°
	Dec. 15, 1948	62°
Omaha, NE	June 11, 1953	77°
	Dec. 11, 1965	59°
Miles City, MT	June 11, 1953	69°
Wichita, KS	Jan. 12, 1960	58°
Port Arthur, TX	Nov. 22, 1973	75°
San Antonio, TX	May 18, 1966	76°
Galveston, TX	June 28, 1952	81°
	June 26, 1952	80°
	Aug. 28, 1951	80°
	Sept. 1, 1954	80°
	Sept. 27, 1958	80°
Grand Island, NE	Aug. 28, 1954	74°
Aberdeen, SD	July 1, 1953	74°
	July 27, 1949	75°
St. Louis, MO	Dec. 15, 1948	62°
Topeka, KS	July 12, 1969	77°
	July 17, 1969	77°
	Jan. 12, 1960	59°
Kansas City, KS	Aug. 6, 1962	77°
	Jan. 12, 1960	59°
	Jan. 30, 1968	58°
Tulsa, OK	Dec. 15, 1948	65°
San Angelo, TX	Apr. 29, 1954	71°
Del Rio, TX	May 23, 1966	75°
Dallas, TX	May 17, 1966	76°
Enid, OK	July 2, 1957	76°
	July 6, 1949	76°
	July 7, 1949	76°
Burlington, IA	July 23, 1965	77°
North Platte, NE	Aug. 29, 1951	71°
Rapid City, SD	June 11, 1953	68°
Victoria, TX	Nov. 27, 1973	75°
Corpus Christi, TX	Sept. 13, 1978	80°
	Sept. 15, 1978	80°
Cut Bank, MT	Jan. 21, 1968	38°

shown as triangles on the example shown in figure 4.2. This was done to insure that excessive envelopment of station data did not occur and that the shape of the curves conformed to the shape determined from the station data.

Figure 4.4 shows comparison of the two analyses for the month of July, the old analysis (dashed lines), and the new analysis (solid lines). In preparing the analysis, three criteria were considered: a) the minimum envelopment possible for the dew-point values from the station curves was desired and considering that

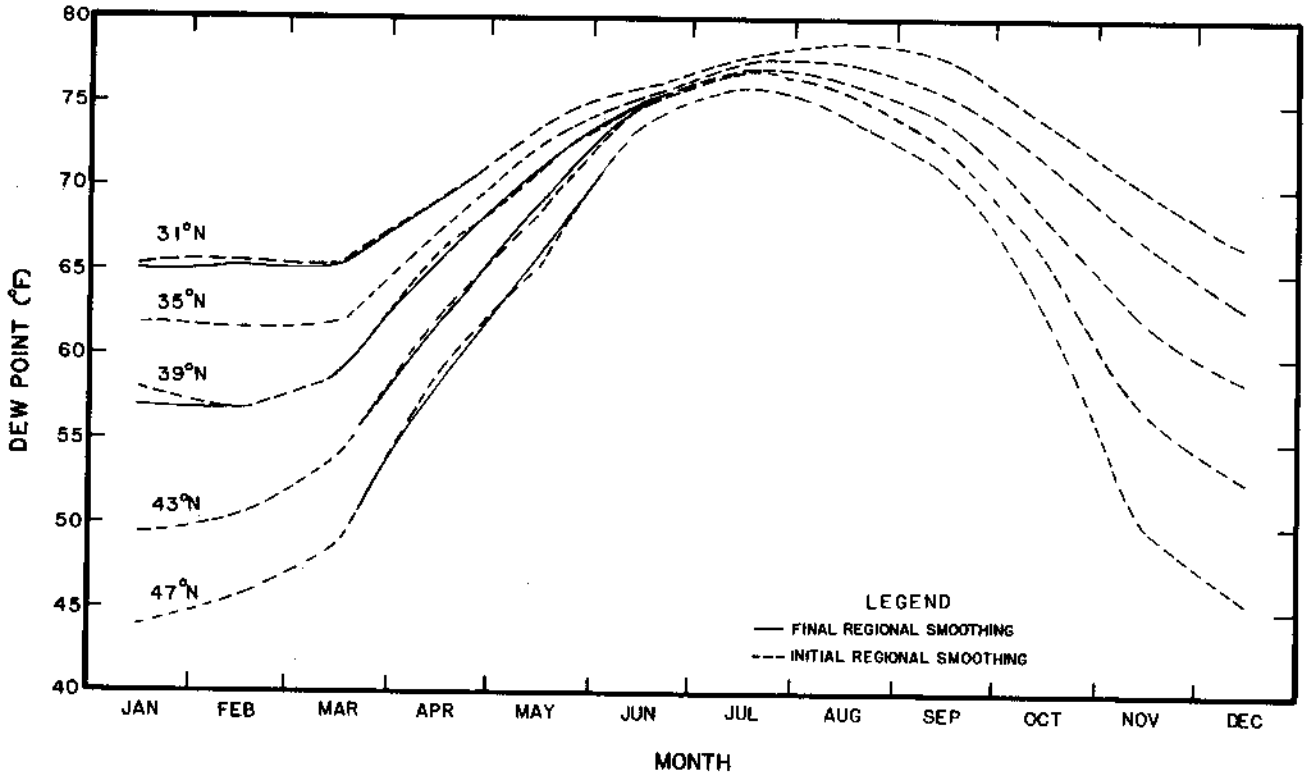


Figure 4.3.--Regional smoothing and consistency checks for maximum persisting 12-hr 1000-mb dew points along the 103rd meridian.

values were plotted only to whole degrees, a variation from the isolines of plus or minus a half degree from station values was allowed; b) values had to be supported by more than a single station within a region; and c) an upper limit of 80 degrees was the highest persisting 12-hr dew point that would be accepted.

Previous analyses have accepted an upper limit of 78 degrees. Earlier, it was considered that the sea-surface temperatures of the warm waters of the Gulf of Mexico in excess of 78 degrees were not sufficient in extent to support moisture through depth for a higher surface dew point. Examination of precipitable water charts for recent periods when surface dew points along the gulf coast were 80 degrees or higher suggested that this lower limit was too restrictive. In particular, the period of mid-September 1978, and early September 1954 suggested that a limit for the maximum dew point of 80 degrees would be appropriate.

4.4 Other Studies

As discussed in section 4.1, maps of maximum persisting 12-hr 1000-mb dew points for the region west of the Continental Divide had been revised in HMR No. 43 (U.S. Weather Bureau 1966) and HMR No. 50 (Hansen and Schwarz 1981). These maps were used as input values along the western edge of the analysis for the present study.

In the case of HMR No. 50, two sets of maps were prepared, one for the general storm and one for the local storm (April to October only). The assumption was made in preparing these two analyses that the local storm resulted partly from a more limited moisture source, that is, recharge from prior precipitation into the local area provided a significant input. Therefore, the moisture charge may be locally larger than for the general storm which required a broad sustained inflow from a moisture source region. Although we have continued the two-storm concept into the region east of the Continental Divide, we chose not to extend the double set of dew point analyses as the differences would be minimal. For those regions where the local storm controls, it is believed that moisture results from inflow somewhat similar to that in the general storm, though in the local storm situation it is more limited in duration and width.

In the Pacific Northwest, the dichotomy between moisture available for the local and general storm was not present and only one set of dew-point charts was prepared. Comparison between dew point values determined from HMR No. 43, in general, showed good agreement with values from the present study. Differences in the dew-point values between the two maps could be attributed to the longer length of record in the present study.

4.5 Revised Seasonal Maps

Revised maps of maximum persisting 12-hr 1000-mb dew points are shown in figures 4.5 through 4.16. These maps were used in the moisture maximization and transposition of storms in the study region. They should be used in any future study for this region until alternate procedures are developed for estimating moisture charge in storms.

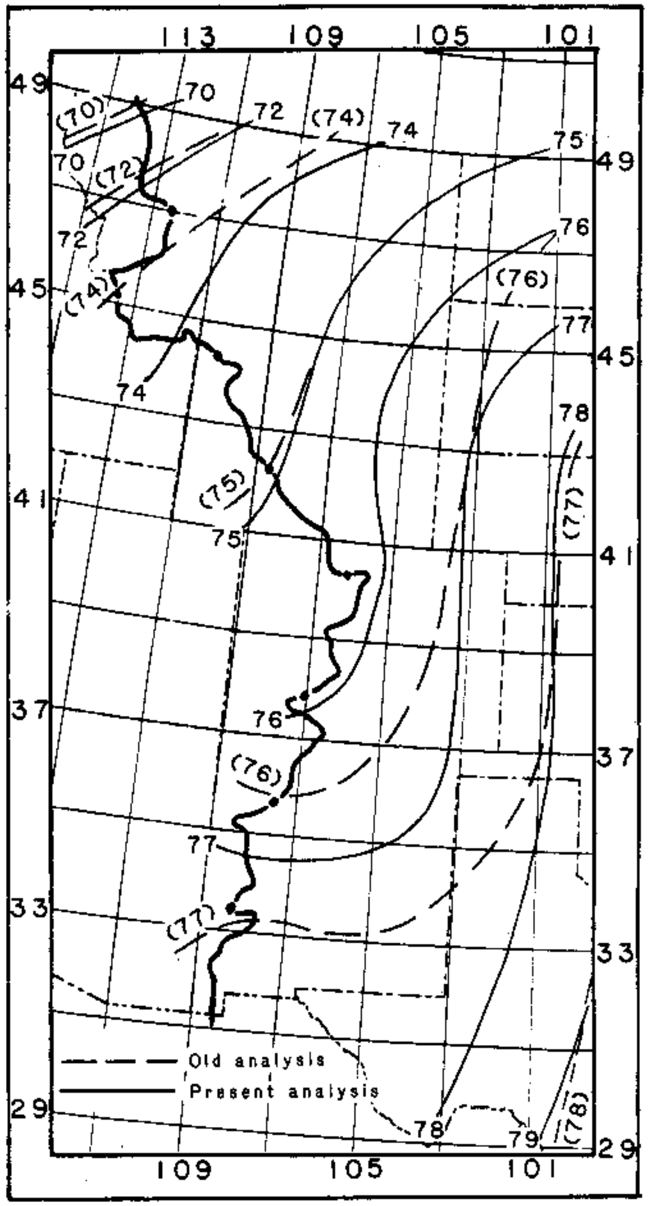


Figure 4.4.--Comparison of mid-July maximum persisting 12-hr 1000-mb dew points from Climatic Atlas of the United States and present study.

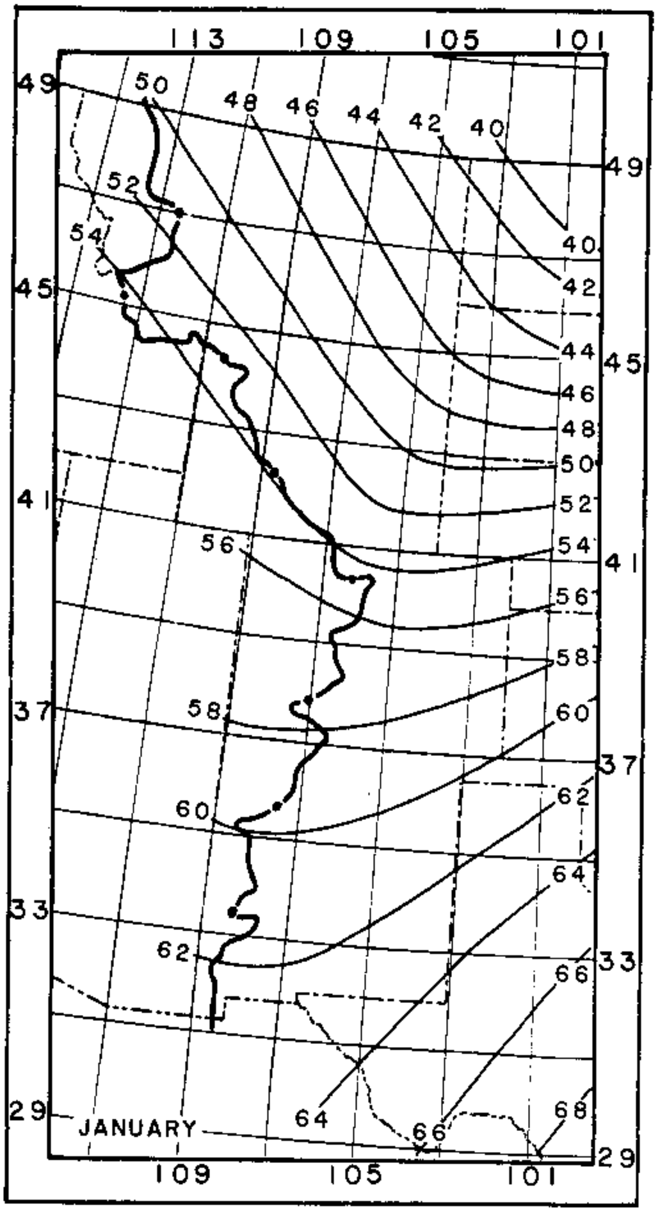


Figure 4.5.--Maximum persisting 12-hr 1000-mb dew points (°F) for January.

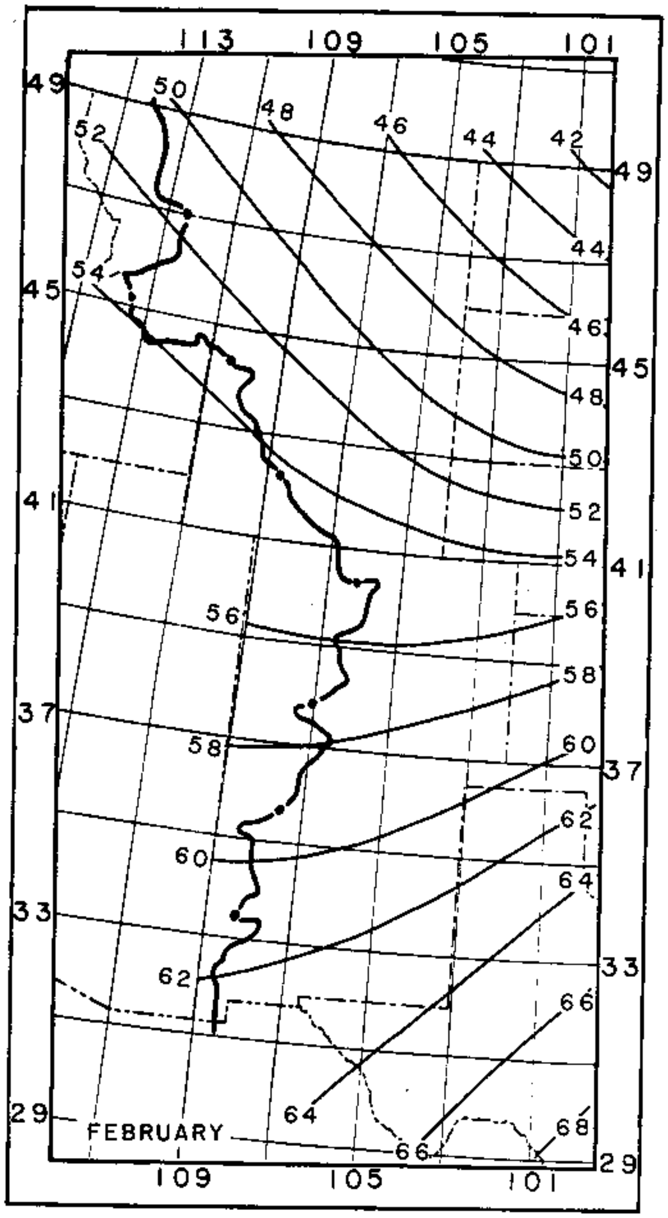


Figure 4.6.--Maximum persisting 12-hr 1000-mb dew points (°F) for February.

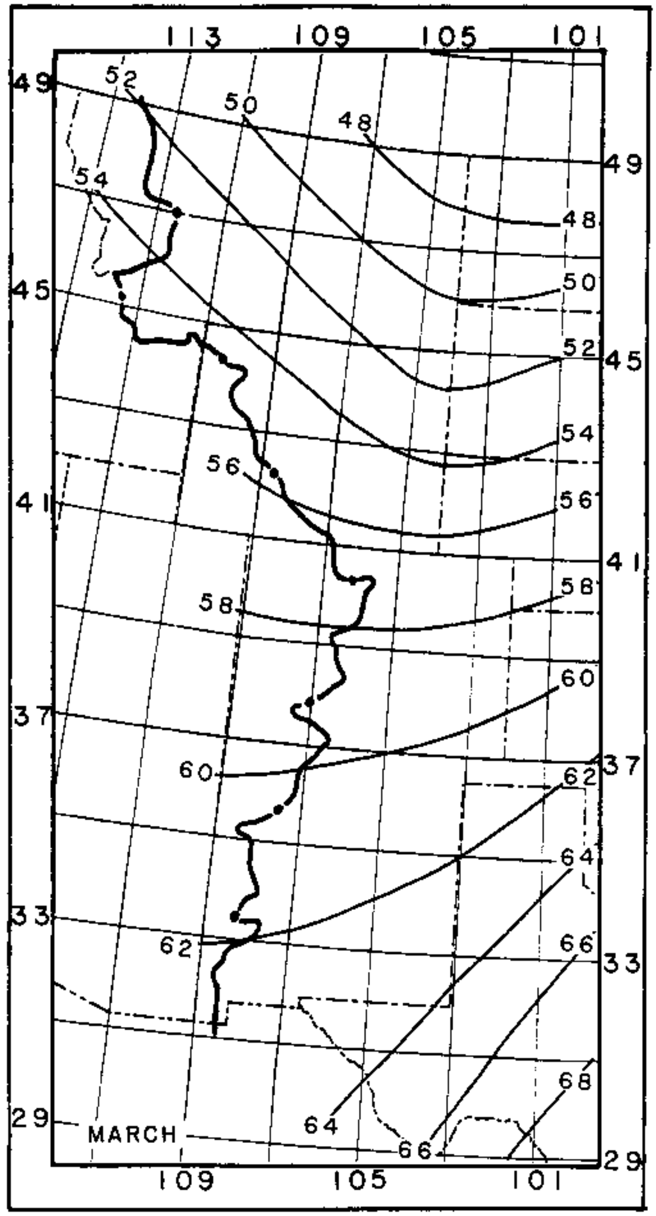


Figure 4.7.--Maximum persisting 12-hr 1000-mb dew points (°F) for March.

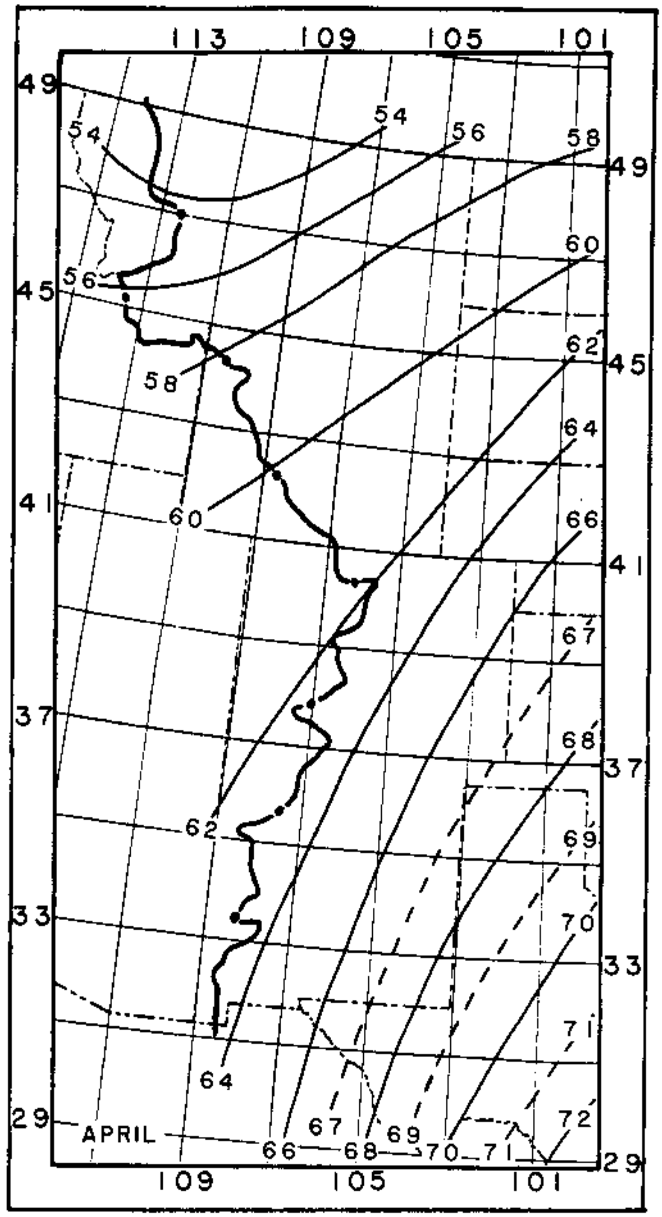


Figure 4.8.--Maximum persisting 12-hr 1000-mb dew points (°F) for April.

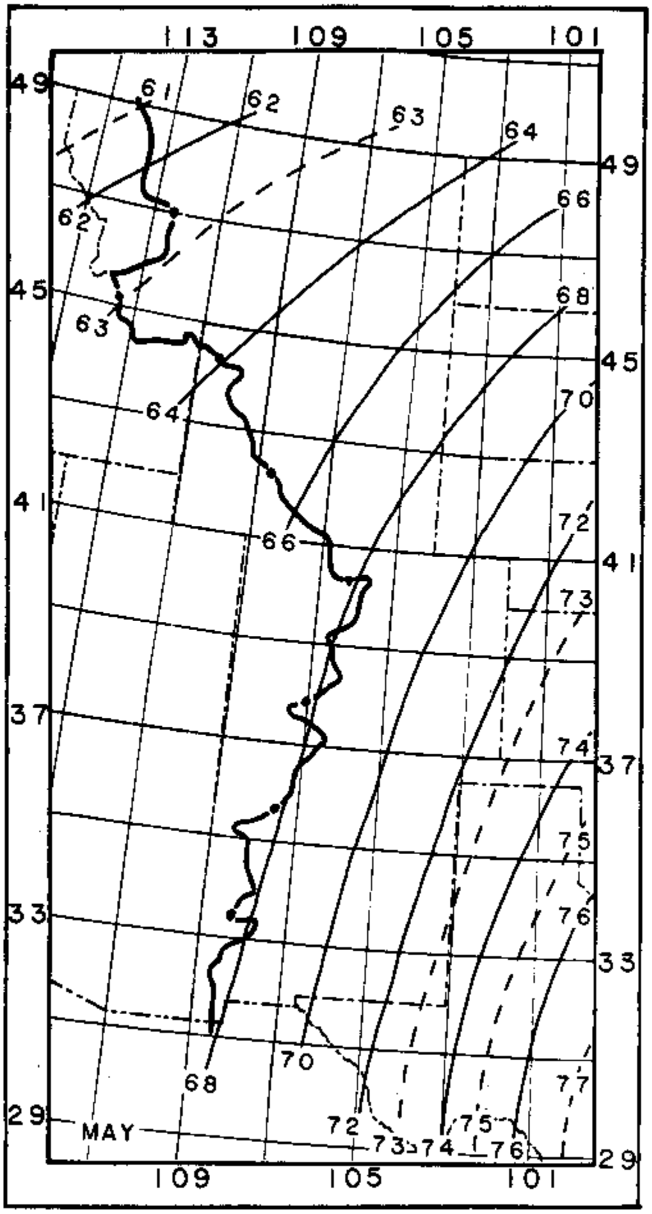


Figure 4.9.--Maximum persisting 12-hr 1000-mb dew points (°F) for May.

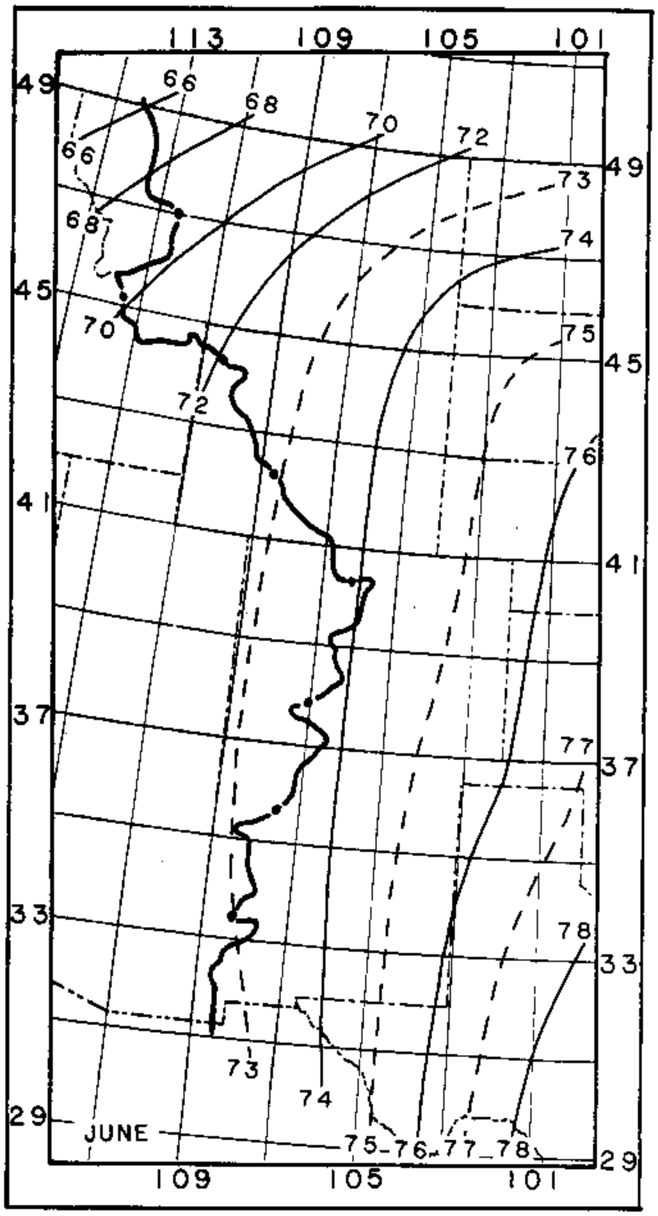


Figure 4.10.--Maximum persisting 12-hr 1000-mb dew points (°F) for June.

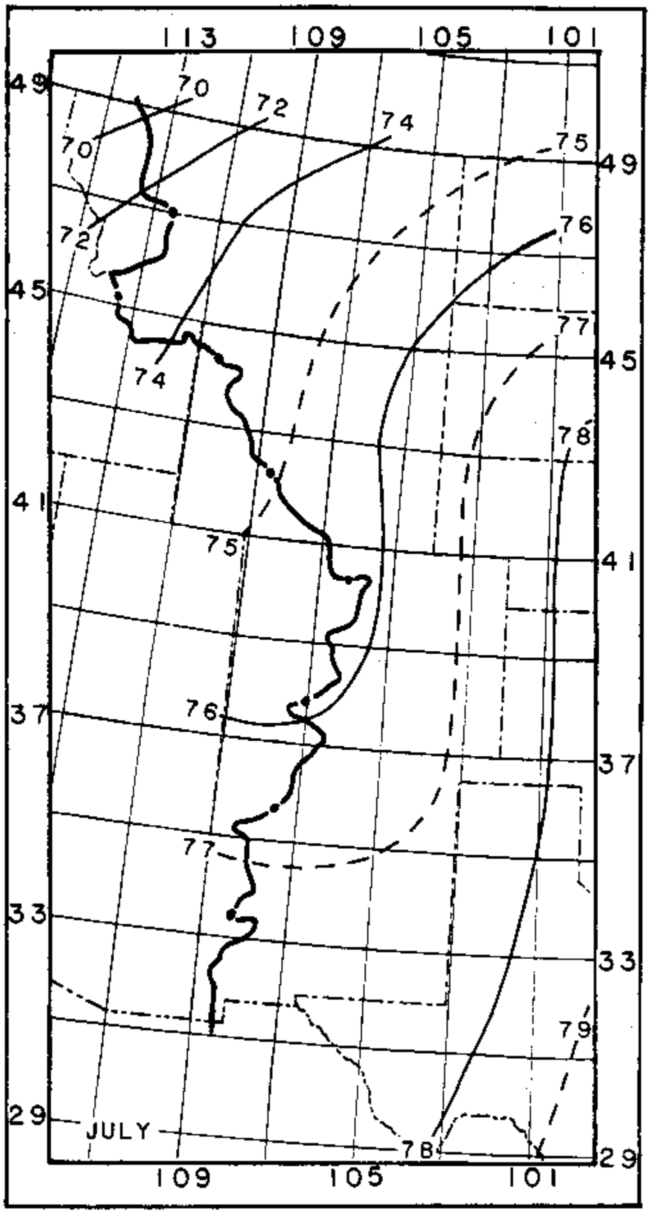


Figure 4.11.--Maximum persisting 12-hr 1000-mb dew points (°F) for July.

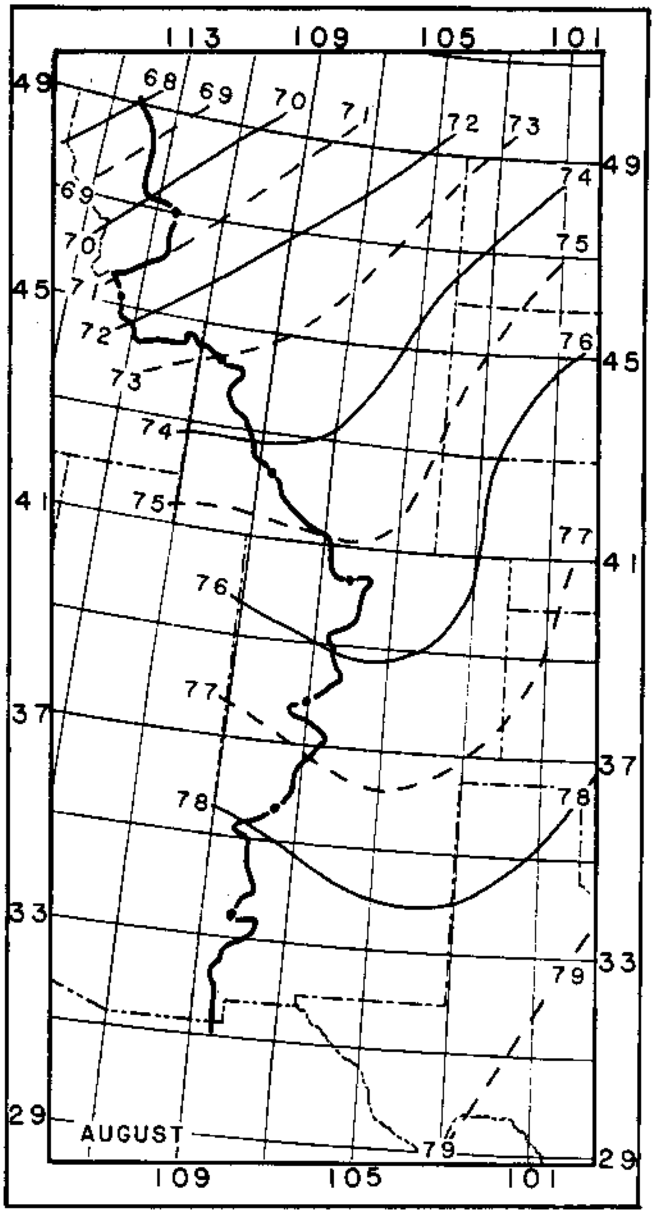
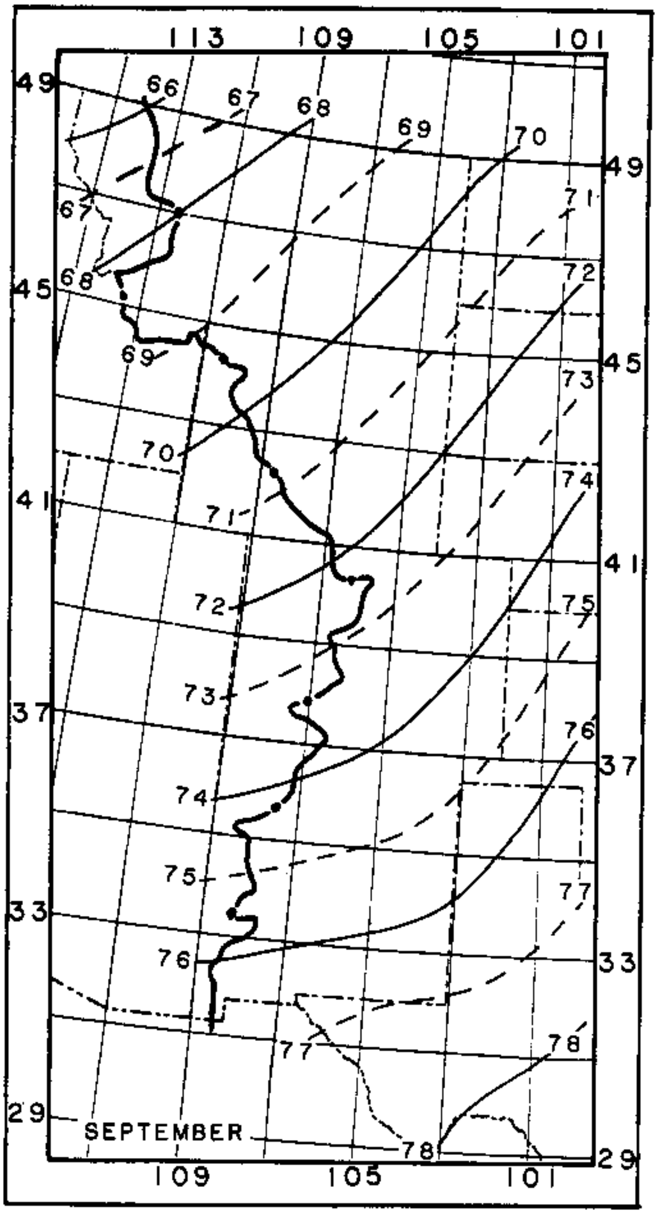


Figure 4.12.--Maximum persisting 12-hr 1000-mb dew points (°F) for August.



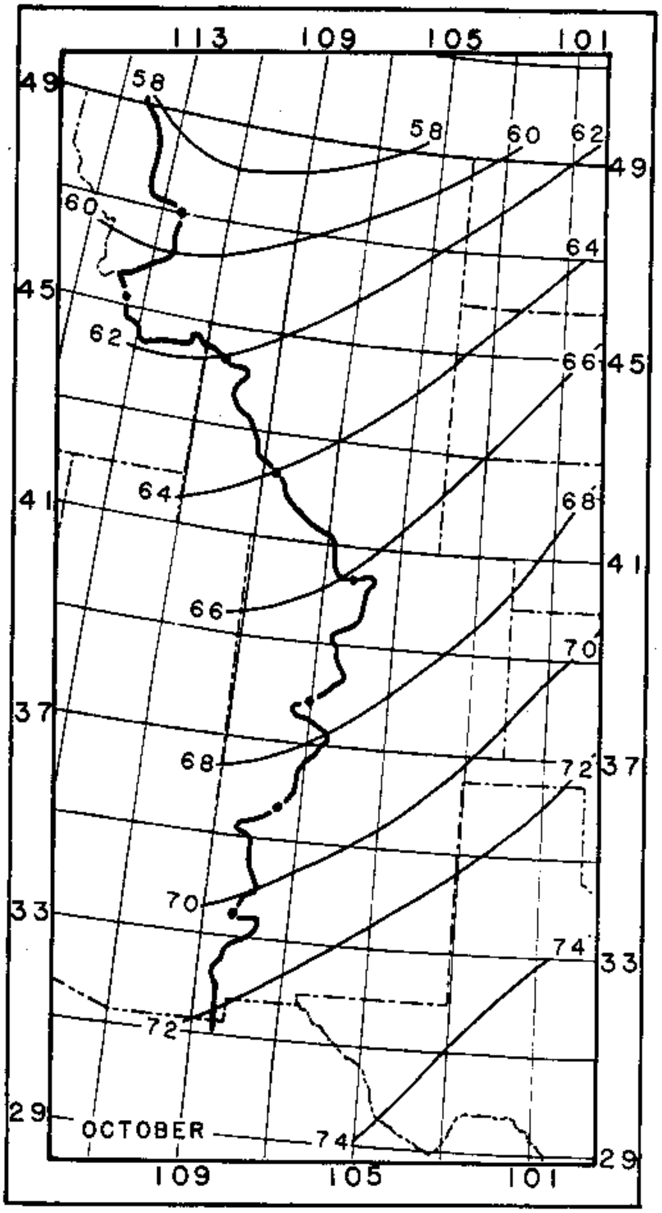


Figure 4.13.—Maximum persisting 12-hr 1000-mb dew points (°F) for September.

Figure 4.14.—Maximum persisting 12-hr 1000-mb dew points (°F) for October.

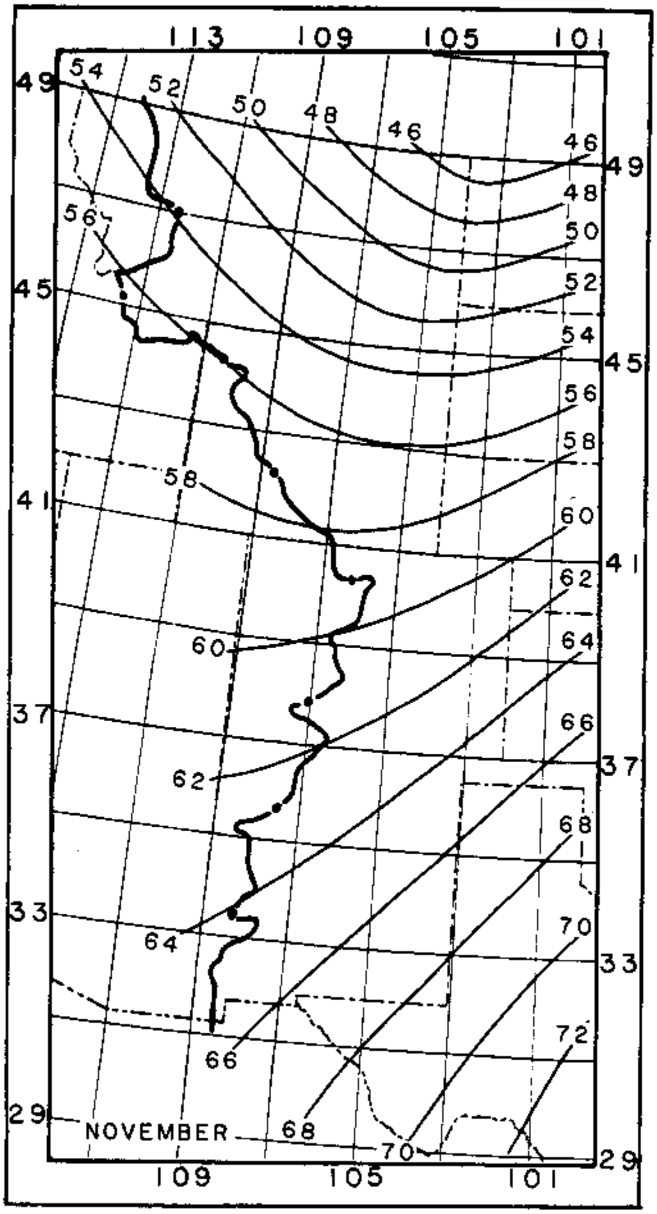


Figure 4.15.--Maximum persisting 12-hr 1000-mb dew points (°F) for November.

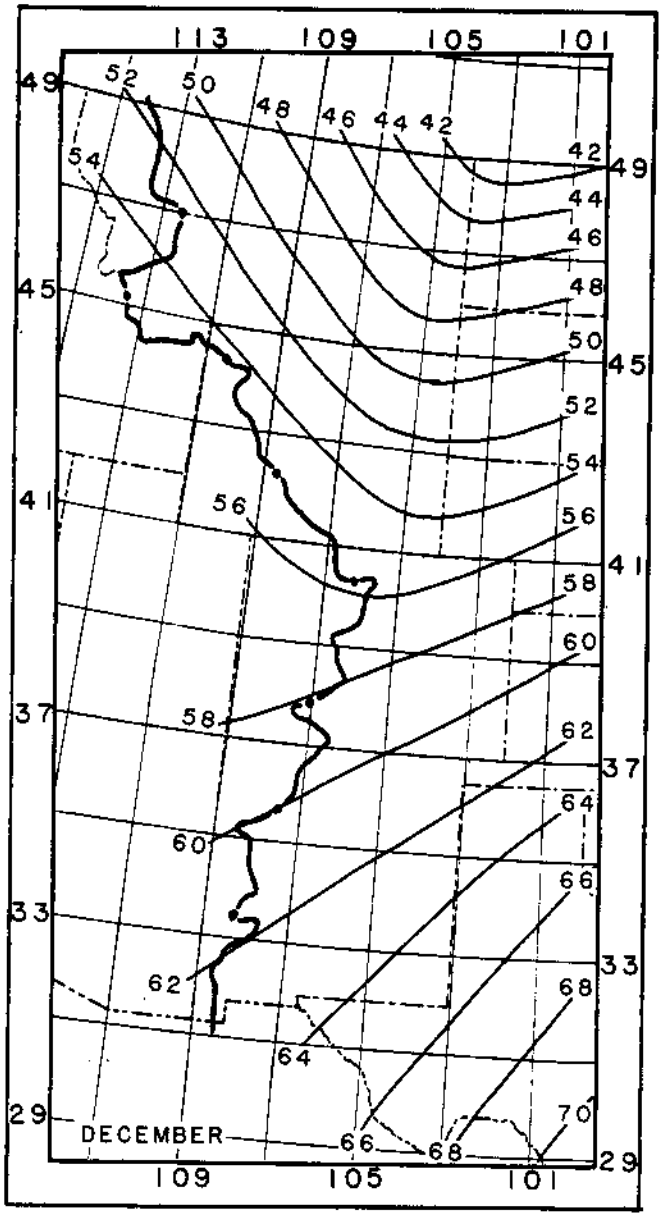


Figure 4.16.--Maximum persisting 12-hr 1000-mb dew points (°F) for December.

5. REPRESENTATIVE PERSISTING 12-HR 1000-MB STORM DEW POINTS

5.1 Introduction

Representative storm dew points were available from other hydrometeorological studies for most of the storms important for determining PMP in the CD-103 region. These dew points were determined at different times by different analysts. Although the same general guidelines were followed, some variability existed in the criteria used. As a result of concern for possible inconsistencies, it was decided that for the present study, all important storms would be reviewed to determine an appropriate representative storm dew point.

5.2 Criteria for Selecting Representative Storm Dew Points

Specific guidelines were formulated for selecting stations used to determine the representative storm dew point in each storm. The guidelines used were:

1. A dew point that was equaled or exceeded for a period of 12 hr, as with previous studies, was selected for each station.

2. A minimum of two stations were to be used. The fewer stations used in averaging the data, the higher the storm dew point obtained, but it was believed that using only one station could be unrepresentative. A single station would be accepted in those cases, however, when the station appeared to represent a narrow tongue of moisture inflow to a small-area precipitation pattern as is typically the case for local storms (chapt. 12), or when no other representative data exist.

3. Stations were to be outside the rain area and along the inflow trajectory. The representative moisture is that which is not influenced by precipitation.

4. Stations in the upwind direction at a time that generally allows transport of the moisture to the precipitation site during a reasonable interval compatible with observed winds in the storm were to be selected.

5. The distance to the stations selected for determining the storm dew point were to be limited to that of synoptic scale phenomena (an outside limit of 1,000 mi has been placed on the reference distance, although almost all storms considered had distances well short of this limit).

6. Stations being evaluated must show observations for almost all reporting periods during the 12-hr period under consideration. This is to say that a station which had missing data for more than half of the 12-hr period being considered could not be included.

5.3 Selection of Representative Storm Dew Points

Using these guidelines, each storm considered important for determining PMP in this region was reviewed. First the synoptic maps were examined to confirm a general inflow trajectory. Then the stations which could be used to obtain a representative persisting 12-hr dew point were judged relative to the trajectory and magnitude of surface dew points (reduced to 1000 mb).

Table 5.1 documents the representative storm dew points that resulted from this review. Additional information is provided for previous storm dew points, date of beginning of the maximum 12-hr period, reference location, representative persisting 12-hr 1000-mb storm dew points for each storm, and the maximum persisting 12-hr 1000-mb dew point (sec. 4.5). A standard practice in hydrometeorological studies is to select the maximum persisting 12-hr 1000-mb dew point 15 days toward the warm season from the date of the storm (Schreiner and Riedel 1978). This was done in this study. This practice recognizes that the date of storm occurrence is not fixed and could be earlier or later than the actual date. The practice will increase the moisture maximization factor 10 to 15 percent.

In table 5.1, "old" refers to the values that were used for these storms prior to this study, whereas "new" refers to the revised value from this study. Twenty-three of the 32 storms with previous storm dew points were revised in some manner. For those storms with no values listed under "old," no previous representative storm dew point was available. The final column in this table lists the code letters for stations averaged to obtain storm dew points. Table 5.2 provides a list of the station names corresponding to the coded entries.

In table 5.1, in addition to those for local storms (chapt. 12), the Belt, MT (71), Virsylvia, NM (35), and Rapid City, SD (78) storm dew points are single station values. As justification for the Belt storm, the station at Glasgow (GGW) was the only station available along a narrow inflow trajectory. No other acceptable data were available for the Virsylvia, NM storm. For the Rapid City storm, the station at Rapid City (RAP) provided the storm dew point. Although the reference distance is particularly short, the dew points at this station satisfied the guidelines set for this study. The dew points were taken prior to the time precipitation began at Rapid City. Again, a relatively narrow moisture band was involved in this storm (Schwarz et al. 1975).

As an example of the process followed in determining storm dew points, figure 5.1 shows the situation for the Cherry Creek, CO storm (47) of May 30-31, 1935. The open arrow depicts the inflow trajectory of maximum moisture showing a rather direct flow from the Gulf of Mexico to the storm location. Four stations, Wichita Falls, Waco, Abilene and Ft. Worth, TX were selected to represent the region of maximum atmospheric moisture. The centroid of the figure formed by connecting these stations is the reference location for this storm. It is 540 mi southeast of the storm site.

The data listed in figure 5.1 give the surface dew points at the four stations reduced to 1000 mb for the period 0000 to 2100, May 30. Before and after this period the dew points are less than those shown. For each observation time the four station values are averaged. The highest 12-hr set of averages occurs between 0600 and 1800. The representative storm dew point is the highest value common to all averaged values for the period. For the Cherry Creek storm, the new storm dew point is 71°F.

Table 5.1.--Representative persisting 12-hr 1000-mb storm and maximum dew points for important storms in and near study region

Storm No.	Name	Storm T_d Old	Storm T_d New	Date+	Ref. Old	Loc. New	Max. T_d Old	Max. T_d New	Stations
1.	Ward District, CO	62	64	30	325SE	350SE	75	77	AMA, DDC
6.	Boxelder, CO	60	60	4	350SE	320SE	72	74	DEN, PUB, DDC, OKC, ICT
8.	Rociada, NM	72	72	28	170SSE	300ESE	76	77	ABI, AMA
10.	Warrick, MT	64	64	6	380ESE	380ESE	73	75	ISN, PIR
13.	Evans, MT	65	65	4	510ESE	510ESE	75	76	BIS, RAP, PIR, VTN, HON
86.	May Valley, CO	67	67	18	450SSE	450SSE	76	76	AMA, ABI, FTW, SAT
20.	Clayton, NM	68	69	1	550SE	560SSE	76	77	SAT, DRT, CRP
23.	Tajique, NM	69	69	21	80SE	160SSE	77	78	ELP, ROW
25.	Lakewood, NM	-	76	7	-	350SE	-	79	DRT, SAT
27.	Meek, NM	72	72	15	390ESE	400ESE	78	79	AMA, ABI, FTW, OKC, SAT, GBK
30.	Fry's Ranch, CO	56	63	15	550ESE	700SE	71	74	FWH, DAL
31.	Penrose, CO	67	70	4	400SE	350SE	77	77	AMA, OKC
32.	Springbrook, MT	71	72	18	500ESE	370ESE	76	77	PIR, HON, FAR
35.	Virsylvia, NM (Cerro)	-	66	17	-	120SW	-	77	ABQ
38.	Savageton, WY	68	72	28	550SE	530SE	75	76	FRI, CNK
44.	Porter, NM	70	71	11	540SE	380SE	78	77	DRT, AUS, FTW, ABI
46.	Kassler, CO	71	66	10	440SE	420SE	77	77	OKC, DDC
47.	Cherry Creek, CO	72	71	30	540SE	560SE	76	79	ABI, ACT, FTW, SPS
101.	Hale, CO	72	71	30	540SE	560SE	76	79	ABI, ACT, FTW, SPS
48.	Las Cruces, NM*	-	71	30	-	-	-	78	ELP
105.	Broome, TX	77	77	14	350SSE	350SSE	78	80	CRP, BRO
53.	Loveland, CO	71	71	1	180SE	210SE	76	76	PUB, GLD
55.	Masonville, CO*	-	65	10	-	-	-	74	AKO
108.	Snyder, TX	73	75	19	100SE	340SSE	78	79	SAT, CRP
56.	Prairieview, NM	70	73	20	390SE	370SE	77	78	SAT, AUS
58.	McColleum Ranch, NM	72	72	21	50SE	300SE	77	79	ELP, DRT, SAT, CRP
60.	Rancho Grande, NM	74	75	31	250SE	250SE	77	78	LBB, BGS, ABI
66.	Ft. Collins, CO	66	67	30	570SE	600SE	78	78	GAG, TUL
67.	Golden, CO*	65	65	7	-	-	76	75	AMA

Table 5.1.--Representative persisting 12-hr 1000-mb storm and maximum dew points for important storms in and near study region (continued)

Storm No.	Name	Storm T_d Old	Storm T_d New	Date+	Ref. Loc. Old	Ref. Loc. New	Max. T_d Old	Max. T_d New	Stations
68.	Dupuyer, MT	63	63	17	600ESE	600ESE	76	77	RAP, MBG, HON, PIR
111.	Del Rio, TX	74	74	24	220SE	220SE	78	80	LRD, BRO, CRP
71.	Belt, MT	-	64	2	-	200ENE	-	71	GGW
112.	Vic Pierce, TX	75	75	26	250SE	250SE	78	80	BRO, CRP, LRD, SAT, DRT, ALI, HRL
72.	Buffalo Gap, Sask.	-	64	29	-	520S	-	74	CYS, BFF
75.	Gibson Dam, MT	64	66	8	310ESE	1000ESE	72	77	CNK, DDC
76.	Plum Creek, CO	71	72	17	300SE	180SSE	76	76	TAD, DHT
114.	Glen Ullin, ND	-	68	24	-	180SE	-	76	HON, ABR
77.	Big Elk Meadow, CO	-	65	7	-	300ESE	-	74	CNK, GLD, DDC
78.	Rapid City, SD	72	72	9	15SE	15SE	74	75	RAP
79.	Broomfield, CO	-	60	6	-	130SE	-	71	PUB, GLD
81.	Big Thompson, CO	-	71	31	-	210ESE	-	77	AKO, GLD, HLC
82.	White Sands, NM	-	67	19	-	60E	-	78	ROW, ELP
116.	Medina, TX	78	77	2	210SE	170SE	78	80	CRP, VCT

Maximum T_d selected 15 days into warm season (see text)
*Criteria for maximum persisting 12-hr 1000-mb dew points were selected at the storm location (sec. 12.3.2.2).
+Date for new storm dew point. See table 2.1 for complete storm date

Table 5.2.--Index to stations used to determine representative persisting 12-hr 1000-mb storm dew points

Three letter ID	Station name	Three letter ID	Station name	Three letter ID	Station name
ABI	Abilene, TX	DDC	Dodge City, KS	ISN	Williston, ND
ABQ	Albuquerque, NM	DEN	Denver, CO	LBB	Lubbock, TX
ABR	Aberdeen, SD	DHT	Dalhart, TX	LRD	Laredo, TX
ACT	Waco, TX	DRT	Del Rio, TX	MBG	Mobridge, SD
AKO	Akron, CO	ELP	El Paso, TX	MLS	Miles City, MT
ALI	Alice, TX	FAR	Fargo, ND	OKC	Oklahoma City, OK
AMA	Amarillo, TX	FRI	Ft. Riley, KS	PIR	Pierre, SD
AUS	Austin, TX	FTW	Ft. Worth, TX	PUB	Pueblo, CO
BFF	Scottsbluff, NE	GAG	Gage, OK	RAP	Rapid City, SD
BGS	Big Springs, TX	GBK	Grosbeck, TX	ROW	Roswell, NM
BIL	Billings, MT	GGW	Glasgow, MT	SAT	San Antonio, TX
BRO	Brownsville, TX	GLD	Goodland, KS	SPS	Wichita Falls, TX
CNK	Concordia, KS	HLC	Hill City, KS	TAD	Trinidad, CO
CRP	Corpus Christi, TX	HON	Huron, SD	TUL	Tulsa, OK
CYS	Cheyenne, WY	HRL	Harlingen, TX	VCT	Victoria, TX
DAL	Dallas, TX	ICT	Wichita, KS	VTN	Valentine, NE

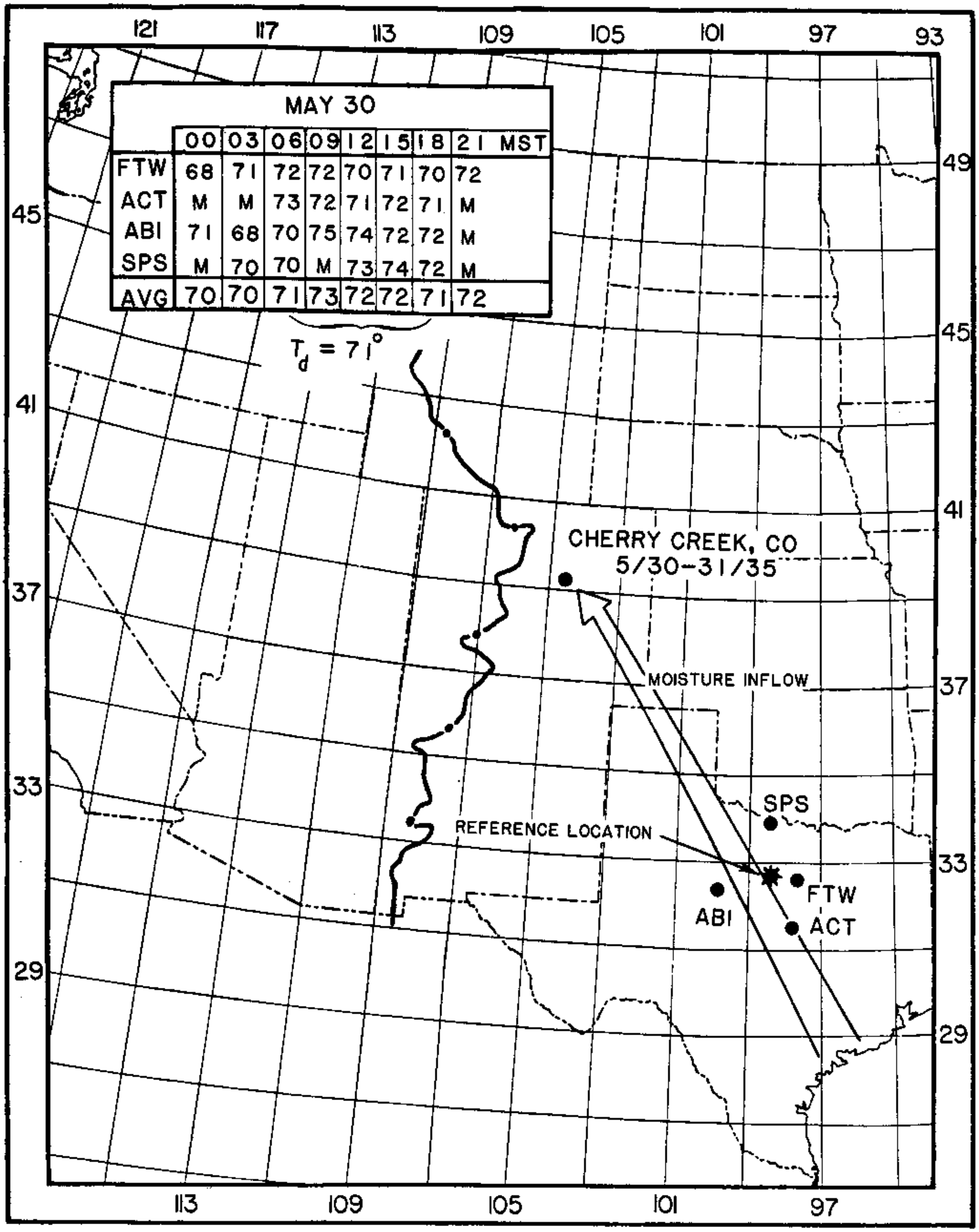


Figure 5.1.—Example of the selection of representative persisting 12-hr storm dew point for the Cherry Creek, CO storm (47) of May 30-31, 1935.

5.4 Storm Moisture Maximization Factors

It has been the practice in hydrometeorology to compute an in-place moisture maximization factor for a storm based on the ratio of precipitable water equivalent of the maximum persisting 12-hr 1000-mb dew point for the date of storm occurrence (plus 15 days) to that of the representative persisting 12-hr 1000-mb dew point. To do so assumes that the storm locations will be at a relatively low elevation (up to about 1500 ft), so that any correction for elevation above 1000 mb will be relatively insignificant. This assumption has been used in many PMP studies and was used for HMR No. 51 (Schreiner and Riedel 1978).

In order to make comparisons with the previously determined moisture maximization factors, new values were computed using the ratio of precipitable water values associated with maximum and representative persisting 12-hr 1000-mb dew points uncorrected for elevation for the storms in table 2.2. This adjustment is shown in table 5.3 (column 2) as the "new" value in percent. The "old" value (column 1) is the one which had previously been used, based on precipitable water values associated with earlier determinations of representative storm and maximum persisting dew points. Since most storms of interest to this study occur at elevations above 3,000 ft, it was necessary to include an elevation consideration in the maximization computations. The maximization factor is a ratio of precipitable waters as before, but the amount of the precipitable water below the effective elevation of the storm site is subtracted. As an example, consider the first storm in table 5.3, Ward District, CO, which occurs at 9,600 ft. From table 5.1, the storm dew point is 64°F at the reference location (reduced to the equivalent 1000-mb value), and the maximum persisting dew point is 77°F (also at the reference location, and 1000-mb elevation). From tables of precipitable water (U.S. Weather Bureau 1951), the precipitable water equivalents for these dew points are 1.69 and 3.19 in., respectively. The ratio of larger to smaller value, uncorrected for elevation, is 189 percent. Considering the elevation of 9,600 ft., precipitable water amounts of 1.92 and 1.17 in. must be subtracted from the numerator and denominator, respectively. Forming the new ratio of 1.27 divided by 0.52 in. results in a maximization factor of 244 percent, a considerable increase from the factor uncorrected for elevation. The elevation corrected adjustment factors for all 43 storms are listed in table 5.3 (column 3).

Concern was expressed in HMR No. 51 for the upper limit to which moisture maximization factors appeared reasonable. In HMR No. 51, factors greater than 150 percent were accepted if the maximized value could be supported reasonably well by surrounding storm depths with lesser adjustments. If no support from surrounding storms was found, a limit of 150 percent was imposed. In the present study a similar consideration was made, and in the nonorographic region east of the orographic separation line the same limit was used. Because of the effect of the elevation correction in raising most adjustment factors, in the more mountainous regions (west of the orographic separation line) a limit was set at 170 percent. In the case of the adjustment factor computed for the example at Ward District, CO, the factor of 244 percent is limited to 170 percent (column 4). The reason for this limitation is discussed more fully in chapter 8.

Table 5.4 lists the 10 largest observed and in-place moisture maximized storm depths for three selected durations and area sizes. The moisture maximized values were obtained by multiplying the observed DAD data by the corresponding moisture adjustment factors from column 3 or 4 of table 5.3, as appropriate. A

Table 5.3.--In-place moisture maximization factors (percent) for important storms in and near the CD-103 region

Storm No.	Name	In-place Moisture maximization adjustment: Sea level or 1000 mb old (1)†	new (2)†	Barrier/elevation actual (3)†	limited (4)†
1.	Ward District, CO	189	189	244	170
6.	Boxelder, CO	181	200	200	170
8.	Rociada, NM	122	128	138	-
10.	Warrick, MT	155	172	188	170
13.	Evans, MT	156	164	191	170
86.	May Valley, CO	155	155	165	-
20.	Clayton, NM	148	148	158	-
23.	Tajique, NM	148	155	177	170
25.	Lakewood, NM	-	115	117	-
27.	Meek, NM	134	140	170	170
30.	Fry's Ranch, CO	210	171	185	170
31.	Penrose, CO	163	141	151	-
32.	Springbrook, MT	128	128	131	-
35.	Virsylvia, NM (Cerro)	-	170	205	170
38.	Savageton, WY	141	122	126	-
44.	Porter, NM	148	134	140	-
46.	Kassler, CO	134	171	193	170
47.	Cherry Creek, CO	122*	147	163	150
101.	Hale, CO	122*	147	156	150
48.	Las Cruces, NM	-	141	148	-
105.	Broome, TX	105	116	117	-
53.	Loveland, CO	128	128	134	-
55.	Masonville, CO	-	156	183	150#
108.	Snyder, TX	128	121	123	-
56.	Prairieview, NM	141	128	132	-
58.	McColleum Ranch, NM	128	140	151	-
60.	Rancho Grande, NM	116	116	119	-
66.	Ft. Collins, CO	179	171	189	170
67.	Golden, CO	172	164	185	150#
68.	Dupuyer, MT	189	199	220	170
111.	Del Rio, TX	121	134	135	-
71.	Belt, MT	-	141	148	-
112.	Vic Pierce, TX	116	127	130	-
72.	Buffalo Gap, Sask.	-	164	172	150
75.	Gibson Dam, MT	148	170	200	170
76.	Plum Creek, CO	128	122	128	-
114.	Glen Ullin, ND	-	148	152	150
77.	Big Elk Meadow, CO	-	156	182	170
78.	Rapid City, SD	110	116	120	-
79.	Broomfield, CO	-	172	194	170

Table 5.3.--In-place moisture maximization factors (percent) for important storms in and near the CD-103 region (continued)

Storm No.	Name	In-place Moisture maximization adjustment			
		Sea level or 1000 mb		Barrier/elevation	
		old (1)†	new (2)†	actual (3)†	limited (4)†
81.	Big Thompson, CO	-	134	148	-
82.	White Sands, NM	-	171	186	170
116.	Medina, TX	110	116	117	-

* Adjustment determined using maximum persisting 12-hr 1000-mb dew point on storm date.

See section 12.3.2.2 for discussion on limitation to moisture adjustment for local storms.

† (1) In-place adjustment based on storm dew points used before this study; assumes station elevation at sea level.

(2) In-place adjustment based on storm dew points as revised and updated for this study; assumes station elevation at sea level.

(3) In-place adjustment in column 2 adjusted for actual elevation of station.

(4) In-place adjustment limit imposed on adjustments in column 3 when limit exceeded.

storm was only shown for a particular area size and duration in table 5.4 if the storm lasted that long or extended to that area size. For example, the Cherry Creek, storm (47) is not shown for the 10-mi^2 area for a duration of 72 hr because the storm only lasted for 24 hr. Similarly for the Gibson Dam, MT storm (75), the total storm duration was only 36 hr. Thus, it is not shown for the 72 hr duration at 10 mi^2 even though the 24-hr moisture maximized amount is larger than all but two of the values listed. Other significant storms such as those at White Sands, NM (82) and over Big Thompson Canyon, CO (81) are not included because of the short duration of the heavy rainfall. Of interest from results shown in table 5.4 is the fact that the three highest ranked storms in each category are comprised of only 10 different storms. These are storms at Cherry Creek, Penrose, Plum Creek and Big Elk Meadow, CO; Springbrook and Gibson Dam, MT; Savageton, WY; and McColleum Ranch, Porter and Clayton, NM. It is reasonable to consider these 10 storms to be the more important storms in the region. Only storms that occurred within the region were ranked; therefore, storms at Hale, CO, Broome and Vic Pierce, TX and Glen Ullin, ND are not included.

Table 5.4.--Ten largest storm depths within CD-103 region for 6-, 24-, and 72-hr durations for 10-, 1,000-, and 10,000-mi^2 areas - observed and moisture maximized in-place, ranked from highest to lowest in each category

Storm number	Name	Amt.	Storm number	Name	Amt.
	Observed			Moisture Maximized	
		6-hr duration			
		10 mi^2			
47.	Cherry Creek, CO	20.6	47.	Cherry Creek, CO	30.9
76.	Plum Creek, CO	11.5	31.	Penrose, CO	15.7
32.	Springbrook, MT	10.5	58.	McColleum Ranch, NM	15.2
31.	Penrose, CO	10.4	76.	Plum Creek, CO	14.7
58.	McColleum Ranch, NM	10.1	32.	Springbrook, MT	13.8
48.	Las Cruces, NM	7.4	48.	Las Cruces, NM	11.0
53.	Loveland, CO	6.4	10.	Warrick, MT	10.2
38.	Savageton, WY	6.0	75.	Gibson Dam, MT	10.2
10.	Warrick, MT	6.0	53.	Loveland, CO	8.6
75.	Gibson Dam, MT	6.0	68.	Dupuyer, MT	7.5
		1,000 mi^2			
32.	Springbrook, MT	7.4	32.	Springbrook, MT	9.7
47.	Cherry Creek, CO	5.8	47.	Cherry Creek, CO	8.7
31.	Penrose, CO	5.4	31.	Penrose, CO	8.2
76.	Plum Creek, CO	5.0	75.	Gibson Dam, MT	7.8
75.	Gibson Dam, MT	4.6	76.	Plum Creek, CO	6.4
44.	Porter, NM	4.1	20.	Clayton, NM	6.2
20.	Clayton, NM	3.9	23.	Tajique, NM	6.1
58.	McColleum Ranch, NM	3.8	10.	Warrick, MT	6.0
38.	Savageton, WY	3.7	58.	McColleum Ranch, NM	5.7
23.	Tajique, NM	3.6	44.	Porter, NM	5.7
		10,000 mi^2			
32.	Springbrook, MT	3.0	75.	Gibson Dam, MT	4.2
75.	Gibson Dam, MT	2.5	32.	Springbrook, MT	3.9
44.	Porter, NM	2.3	31.	Penrose, CO	3.2
31.	Penrose, CO	2.1	44.	Porter, NM	3.2
76.	Plum Creek, CO	2.0	20.	Clayton, NM	3.2
20.	Clayton, NM	2.0	58.	McColleum Ranch, NM	3.0
58.	McColleum Ranch, NM	2.0	10.	Warrick, MT	2.9
10.	Warrick, MT	1.7	79.	Broomfield, CO	2.4
60.	Rancho Grande, NM	1.7	27.	Meek, NM	2.7
38.	Savageton, WY	1.6	76.	Plum Creek, CO	2.6*

Table 5.4.--Ten largest storm depths within CD-103 region for 6-, 24-, and 72-hr durations for 10-, 1,000-, and 10,000-mi^2 areas - observed and moisture maximized in-place, ranked from highest to lowest in each category (continued)

Storm number	Name	Amt.	Storm number	Name	Amt.
	Observed			Moisture Maximized	
		24-hr duration			
		$10\ mi^2$			
47.	Cherry Creek, CO	22.2	47.	Cherry Creek, CO	33.3
75.	Gibson Dam, MT	14.9	75.	Gibson Dam, MT	25.3
32.	Springbrook, MT	13.3	77.	Big Elk Meadow, CO	20.1
76.	Plum Creek, CO	13.2	58.	McColleum Ranch, NM	18.3
58.	McColleum Ranch, NM	12.1	31.	Penrose, CO	18.1
31.	Penrose, CO	12.0	32.	Springbrook, MT	17.4
77.	Big Elk Meadow, CO	11.8	10.	Warrick, MT	17.3
10.	Warrick, MT	10.2	76.	Plum Creek, CO	16.9
44.	Porter, NM	9.9	68.	Dupuyer, MT	14.6
38.	Savageton, WY	9.5	20.	Clayton, NM	14.2
		$1,000\ mi^2$			
75.	Gibson Dam, MT	12.3	75.	Gibson Dam, MT	20.9
32.	Springbrook, MT	11.3	32.	Springbrook, MT	14.8
76.	Plum Creek, CO	9.5	20.	Clayton, NM	12.5
20.	Clayton, NM	7.9	76.	Plum Creek, CO	12.2
31.	Penrose, CO	7.8	31.	Penrose, CO	11.8
47.	Cherry Creek, CO	7.2	10.	Warrick, MT	11.4
44.	Porter, NM	7.2	47.	Cherry Creek, CO	10.8
60.	Rancho Grande, NM	6.8	44.	Porter, NM	10.1
10.	Warrick, MT	6.7	68.	Dupuyer, MT	9.5
38.	Savageton, WY	6.6	58.	McColleum Ranch;, NM	9.5
		$10,000\ mi^2$			
75.	Gibson Dam, MT	7.2	75.	Gibson Dam, MT	12.2
32.	Springbrook, MT	5.6	20.	Clayton, NM	8.2
20.	Clayton, NM	5.2	32.	Springbrook, MT	7.3
60.	Rancho Grande, NM	4.9	58.	McColleum Ranch, NM	6.3
44.	Porter, NM	4.5	44.	Porter, NM	6.3
58.	McColleum Ranch, NM	4.2	27.	Meek, NM	6.1
76.	Plum Creek, CO	3.9	1.	Ward District, CO	6.0
8.	Rociada, NM	3.8	13.	Evans, MT	5.8
31.	Penrose, CO	3.6	10.	Warrick, MT	5.8
27.	Meek, NM	3.6	60.	Rancho Grande, CO	5.8

Table 5.4.--Ten largest storm depths within CD-103 region for 6-, 24-, and 72-hr durations for 10-, 1,000-, and 10,000-mi^2 areas - observed and moisture maximized in-place, ranked from highest to lowest in each category (continued)

Storm number	Name	Amt.	Storm number	Name	Amt.
	Observed			Moisture Maximized	
		72-hr duration			
		$10\ mi^2$			
58	McColleum Ranch, NM	21.2	58.	McColleum Ranch, NM	32.0
77.	Big Elk Meadow, CO	17.8	72.	Big Elk Meadow, CO	30.3
38.	Savageton, WY	16.9	76.	Plum Creek, CO	21.4
76.	Plum Creek, CO	16.7	38.	Savageton, WY	21.3
32.	Springbrook, MT	14.6	32.	Springbrook, MT	19.1
31.	Penrose, CO	12.0	31.	Penrose, CO	18.1
53.	Loveland, CO	10.6	53.	Loveland, CO	14.2
56.	Prairieview, NM	8.4	13.	Evans, MT	13.6
60.	Rancho Grande, NM	8.0	56.	Prairieview, NM	11.1
13.	Evans, MT	8.0	23.	Tajique, NM	11.0
		$1,000\ mi^2$			
32.	Springbrook, MT	12.5	72.	Big Elk Meadow, CO	17.3
76.	Plum Creek, CO	12.3	32.	Springbrook, MT	16.4
38.	Savageton, WY	11.8	76.	Plum Creek, CO	15.7
77.	Big Elk Meadown, CO	10.0	38.	Savageton, WY	14.9
58.	McColleum Ranch, NM	9.6	58.	McColleum Ranch, NM	14.5
31.	Penrose, CO	8.7	31.	Penrose, CO	13.1
56.	Prairieview, NM	7.5	23.	Evans, MT	11.7
60.	Rancho Grande, NM	7.2	56.	Prairieview, NM	9.9
13.	Evans, MT	6.9	23.	Tajique, NM	9.0
8.	Rociada, NM	6.5	8.	Rociada, NM	9.0
		$10,000\ mi^2$			
32.	Springbrook, MT	7.7	58.	McColleum Rch., NM	10.6
58.	McColleum Ranch, NM	7.0	32.	Springbrook, MT	10.1
38.	Savageton, WY	6.3	31.	Penrose, CO	8.3
76.	Plum Creek, CO	6.1	13.	Evans, MT	8.0
56.	Prairieview, NM	5.9	38.	Savageton, WY	7.9
60.	Rancho Grande, NM	5.7	76.	Plum Creek, CO	7.8
8.	Rociada, NM	5.6	56.	Prairieview, NM	7.8
31.	Penrose, CO	5.5	8.	Rociada, NM	7.7
13.	Evans, MT	4.7	60.	Rancho Grande, NM	6.8
53.	Loveland, CO	3.5	23.	Tajique, NM	4.9